RELATIONAL BASIS OF THE ORGANISM'S SELF-ORGANIZATION

A Philosophical Discussion

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

In this thesis, I discuss the organism's self-organization from the perspective of relational ontology. I critically examine scientific and philosophical sources that appeal to the concept of self-organization. By doing this, I aim to carry out a thorough investigation into the underlying reasons of emergent order within the ontogeny of the organism. Moreover, I focus on the relation between universal dynamics of organization and the organization of living systems.

I provide a historical review of the development of modern ideas related to self-organization. These ideas have been developed in relation to various research areas including thermodynamics, molecular biology, developmental biology, systems theory, and so on. In order to develop a systematic understanding of the concept, I propose a conceptual distinction between transitional self-organization and regulative self-organization. The former refers to the spontaneous emergence of order, whereas the latter refers to the self-maintaining characteristic of the living systems. I show the relation between these two types of organization within biological processes.

I offer a critical analysis of various theories within the organizational approach. Several ideas and notions in these theories originate from the early studies in cybernetics. More recently, autopoiesis and the theory of biological autonomy asserted certain claims that were critical toward the ideas related to self-organization. I advocate a general theory of self-organization against these criticisms.

I also examine the hierarchical nature of the organism's organization, as this is essential to understand regulative self-organization. I consider the reciprocal relation between bottom-up and top-down dynamics of organization as the basis of the organism's individuation. To prove this idea, I appeal to biological research on

molecular self-assembly, pattern formation (including reaction-diffusion systems), and the self-organized characteristic of the immune system.

Finally, I promote the idea of diachronic emergence by drawing support from biological self-organization. I discuss the ideas related to constraints, potentiality, and dynamic form in an attempt to reveal the emergent nature of the organism. To demonstrate the dynamicity of form, I examine research into biological oscillators. I draw the following conclusions: synchronic condition of the organism is irreducibly processual and relational, and this is the basis of the organism's potentiality for various organizational states.

Table of Contents

List of Figures

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General Introduction

This thesis will address the emergent nature of the organism as an ontogenetic process. A main idea is that emergence is ontological, which requires a new understanding of causation concerning part-whole relations.[1] I criticize the attitude to neutralize emergence based on analysing the organization of a whole as an arrangement of parts in the spatial context, and a deterministic input-output relation in the temporal context (see Chapter 4). Considering the problems such as non-locality in physics, reducing emergence to a matter of arrangement of parts does not provide an exhaustive solution to all the relevant philosophical implications. There are problems that remain unsolved because of the atomistic conception of parts according to which interrelations are considered subsidiary and external. In my thesis, I criticize this mechanistic conceptualization and consider the unsolved causal basis as a fulcrum of my discussion of the organism. On this basis, I postulate that there is a limit to localize the sub-components of a relational whole. This implies that a whole cannot be reduced to the sum of its parts because parts are not distinct from each other as static entities. Instead, the whole is laden with a constant state of potentiality so that there is a certain extent of indeterminateness within the part-whole relations. As this is a postulate, I do not develop a comprehensive argument that demonstrates an indisputable link between

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[1] Another aspect of the investigation into causation is circular causality that has significant implications for temporality. A cause precedes its effect. However, a feedback loop adds a convoluted situation to the temporal order of a basic cause-effect relation. In the case of a feedback loop, the effect of a cause affects the initial causal agent resulting in a circular synergetic situation from the initial cause-effect relation. In selected effects, or similarly, in second order causation, a similar convoluted situation is involved. In these types of causation, the effect of a cause is its persistence over time (Hitchcock, 1996). This is explicit in the case of natural selection, but in fact selected effects are also evident through part-whole relations within the organism. In this case, the part affect the whole, but this is contextual to the whole that determines whether the initial causal relations will be maintained among alternative paths of development. Of course, feedback loops and selected effects do not imply a direct anomaly in the temporal order of causal relations; instead they are cases of complexification and self-maintenance. However, circular causation might also have more profound implications concerning the unsolved problems of causation (see: Heylighen, 2010).

biological research and more puzzling questions of physics.[2] Rather, my argument relates to questions in modern physics indirectly, and mainly addresses the issues in biology. I argue that the limit to localize the parts of a relational whole is evident in the potentiality of relations in the ontogeny of the organism. Moreover, the self-organization of the organism is possible due to this relational basis of producing organizational potentials. The elaboration of my argument will mostly consider biological processes, whereas in this introduction, I aim to clarify certain points concerning a broader context that involves general philosophical claims.

In this thesis, I discuss the question of ontogeny within two different implicit dimensions. One of them concerns a discussion in philosophy of biology, namely, a critical attitude toward the neo-Darwinian paradigm, which is prevalent in several contemporary areas of research including levels of selection, neutral theory of molecular evolution, evolutionary developmental biology, systems biology, etc. Self-organization provides support to the critique of neo-Darwinism by emphasizing that the organism's form is not solely determined by natural selection. In addition to the role of selective pressures, self-organization emphasizes the internal relationality of the organism. Moreover, it is related to the idea that form is not predetermined by genes, but it is acquired through the ontogeny on a basis of contingency. The other dimension of this thesis relates to a broader context concerning the nature of causation. Self-organization defines a causal capacity emerging in dissipative systems, whose understanding helps to challenge the notion of inert matter. In dissipative systems, the components become sensitive to the rest of reactions. As Prigogine and Stengers (1984/2017) state: "In equilibrium the matter is blind, but in far-from-equilibrium conditions begins to be able to perceive, to take into account, in its way of functioning, differences in the external world" (p. 14). This is a core idea in self-organization that supports a critique of inert matter in favour of emergence. In this thesis, I examine this idea in relation to

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[2] Despite this, the ideas concerning quantum non-locality is a source of inspiration for the argument in this thesis. The idea has gained support due to John Bell's research, which demonstrated that local hidden variables do not extensively underlie statistical results with entangled particles. Brandon and Carson (1996) claim that the argument against hidden variables also supports an indeterminist view concerning biological processes. A discussion of determinism based on the research in physics is not within the scope of this thesis, and therefore I will not go into the details of their argument.

the emergent nature of the organism. I argue that the ontogeny of the organism is a process which is determined by potentiality through interrelations that can produce different organizational networks. This argument involves the application of relational ontology to the organism's self-organization.

Let me first explain the dimension that relates to philosophy of biology. In a classic paper within the critique of the adaptationist programme, Gould and Lewontin (1979) argue that the neo-Darwinist view gave up Darwin's pluralism towards the underlying reasons of evolution, and ascribed any evolutionary change to natural selection, sometimes even at the expense of accepting speculative tales about possible factors that created selective pressure. They claim that, contrary to this attitude, "organisms must be analysed as integrated wholes" (Gould & Lewontin, 1979, p. 147). They also remark that the attitude they promote was once dominant in Continental Europe under the name of developmental morphology, which investigated *Baupläne* of species based on internal constraints. This research perspective was later overshadowed by the adaptationist programme. A similar attitude was held in the research of D'Arcy Thompson. Thompson examined the mathematical basis of physical dynamics that created certain geometrical forms in living systems. However, contrary to the contemporary ideas on self-organization, Thompson developed his theory not as a complement, but as an alternative to Darwinian theory. The research perspective focusing on the organic form has gained a new dimension with the discovery of nonlinear dynamics, which also involved a step toward a broader and unified understanding of self-organization. This is supported by research into feedback processes, self-catalysing chemical activities, and formation of patterns due to responses toward external gradients. This research has not only offered support to the view that biological form is dependent on internal constraints, but also that it is a generative process through the relation between internal and external. Researchers such as Brian Goodwin and Stuart Newman are among the pioneers of this new understanding concerning biological self-organization.

Another relevant perspective within the philosophy of biology is the organizational approach, which promoted the notion of biological autonomy. Theories of cybernetics and autopoiesis are considered within the scope of this perspective, and more recently, the theory of biological autonomy developed by Moreno and Mossio – referred to as *the autonomous perspective* – reinterprets the claims of autopoiesis and the notion of closure in particular (Ruiz-Mirazo & Moreno, 2012; Mossio, Bich, & Moreno, 2013; Moreno & Mossio, 2015). Although I embrace a critical attitude towards some of the ideas in these theories (see Chapter 2), the general position of organizational approach is essential to develop an organism-based alternative against reductionist and gene-centric explanations. Criticism of preformationism characterizes another aspect of this position. Against the preformationist idea that the organism is genetically determined, which denies the organicist dimension of organization by reducing it to theories of molecular biology, I draw support from the modern account of epigenesis, which emphasizes that processes in higher levels are also essential for the organism's form (Moss, 2003).[3] In a similar vein, developmental systems theory (DST) asserts that form is acquired through ontogeny (Oyama et al. 2000; Oyama, 2001a), and the organism is self-organized on a contingent basis (Griffiths & Gray, 1997). I broadly agree with these ideas, however I shall argue that the role of contingency is overestimated and morphogenetic basis of formal stability is underestimated in DST (see Chapter 4).

The abovementioned developments relate to the self-organization at the organism level, whereas relationality also has consequences in a broader context. This brings us to the other dimension of this thesis. In this regard, the main issue of this thesis is the role of self-organization in ontogeny in relation to a critical analysis of causation.[4] The underlying philosophical theme here is relational ontology and its consequences for living systems. In the specific context of self-organization, relationality refers to emerging reciprocal relations within a complex system, and any type of pattern formation or self-constraining effects. Not only biological

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[3] The reason for referring especially to its modern conception is that the original ideas of epigenesis can be traced back to Aristotle. In the beginning of the modern theory, Hans Driesch's ideas on embryonic development, which also promotes an attitude based on potentiality, is fundamental.

[4] Here, instead of specific problems of causation in modern philosophy such as explanation versus causation, Bayesian models, or transitivity, the mentioned aspect relates to reconsideration of causation in relation to an ontological understanding of diachronic emergence. This also involves the implications of process philosophy, e.g. temporality of form (see Chapter 4).

processes in population dynamics and ecosystems, but also physical and chemical processes involve certain outcomes of relationality, which usually arise as spontaneous order in the relevant systems. Stuart Kauffman's (1993) work which investigates spontaneous order is well known. He put forward an extensive theory of relationality in population dynamics by appealing to the notion of self-organization. In his approach, self-organization denotes the emerging order in population dynamics due to epistatic relations between genes. Beyond this, Kauffman (1996, 2000) uses self-organization in the context of a universal tendency for the self-constraining character of energy flow. I use the concept of self-organization in a similar way to that of Kauffman's work, and I think his approach is fundamental for any attempt to understand self-organization. Despite this, I will not discuss the details of Kauffman's *Nk* model in my review in the first two chapters because, in my opinion, a review on point in terms of both the negative and positive aspects of Kauffman's theory is already given by Moss (2003). Here, Moss points out that Kauffman's work is valuable due to demonstrating the far-from-equilibrium nature of life and identifying the role of epigenetic mechanisms as opposed to genetic reductionism. However, Moss claims that Kauffman's work still exhibits instrumental reductionism because it oversimplifies the implications of "wet biology" beyond the epigenetic dimension of life. Relationality between genes is included in *Nk* model (*N* denotes the number of genes, and *k* denotes the number of relations between genes), but obviously genes do not function due to inputs from other genes in real biological processes, in discordance with the represented relations in Kauffman's model (Moss, 2003, pp. 98-107).

New ways of understanding causal relations that are also essential for the study of living systems, such as nonlinear dynamics, call into question the mechanistic understanding of causality, and compel us to seek new philosophical perspectives. One of the theoretical approaches put forward to grasp the causal nature of life in contemporary philosophy of science is based on mechanisms. This new approach of mechanicism, which emerged as a post-positivist philosophy, has attempted to analyse complex systems with nonlinear characteristics in relation to an entity-based approach in part-whole relationships. This approach examines the issues such as modularity, aggregativity, levels of organization, type-token distinction, etc. (Wimsatt, 1997; Menzies, 2012; Craver & Darden, 2013). Although these are genuine problems – some of which are addressed in this thesis – and the solutions offered by the mechanistic approach are successful to a certain degree, new mechanicism does not address the essential problems specific to the self-organization of the organism. This is because of an implicit reconciliation with the traditional claims of Cartesian philosophy. New mechanicism acknowledges that life is a matter of organization. Yet, this approach presupposes that non-living matter is inert, and life is primarily a matter of mechanistic configurations of certain elements within the relevant systems. As matter is considered inert, the dynamicity of relations is extrinsic to static entities. Even though philosophy of mechanisms attempts to examine the processual nature of things within the scope of complexity research, an underlying claim of substance ontology is either directly endorsed, or left unquestioned in this approach. Thus, a mild Cartesianism permeates through the conceptualization of lower-level components that constitute the “parts” of a whole, or the “matter” of an organized system. A dualism between static entities and dynamic relations characterizes the relevant worldview. A proponent of this view might claim that the analysis of mechanisms is free from theory-laden assertions because it is only concerned with the empirical basis of things. In fact, this dualism itself is a hidden theory-laden source that is implicitly endorsed in many supposedly natural accounts. This is indicative of the influence of substance ontology residing in the roots of Western philosophy.

Process philosophy criticizes this atomistic understanding by claiming that a constant state of flux underlies what appears as static. In process philosophy, a landmark study, in which ontological status of the organism is central, was developed by Alfred N. Whitehead. Whitehead was critical of the Newtonian approach that considered matter as purposeless, relationality as external, and temporality as the succession of durationless instants (Desmet & Irvine, 2018). For instance, Whitehead (1934/2011) considered the theory of electromagnetism as a remedy for the restrictions of the Newtonian view, as the former depends on a general field of force. Over time, Whitehead’s philosophy appealed to some theoretical studies in biology, whereas it is hard to say that a widespread application of the philosopher's ideas holds. A more recent development has occurred in philosophy of biology, as Dupré and Nicholson (2018) offered to reform this field in line with a process ontology. In addition, some other studies offered a similar perspective both in philosophy of biology and general philosophy of science, focusing on replacing substance ontology with process ontology (Salmon, 1984; Seibt, 1990; Dupré, 2012). The general implications of these studies in process philosophy support my arguments in this thesis. In particular, Whitehead's alternative approach that emphasizes relationality as well as processuality is valuable. Although not necessarily by examining Whitehead's views in detail,[5] I aim to contribute to process ontology by focusing on the relationality aspect of the organism. In other words, I will promote the idea that things are not only processual, but also relational. In contrast with the abovementioned mechanistic dualism between static entities and dynamic relations, I think a radical reconceptualization of relationality concerning the nature of causation is necessary. What appears as an entity is a product of relationality. In other words, things are nothing but relations. The implication of this statement can only be understood from the viewpoint of process philosophy. Relationality cannot be established without temporality, hence a better way of phrasing relations would be relationing. It should be emphasized that claiming that everything consists of relations is different from claiming that everything is in relation with each other, as the latter does not challenge the atomistic conception of things. The former claim suggests that things are actualized through relationing: there are no absolute properties of things that can actualize in a context-independent way. The self cannot exist without its relation to the non-self.

This might seem controversial to common sense. We refer to relations between the object and the subject, or between the part and the whole, but it is also possible to conceptualize the object or the part as isolated from any relationality. In fact, an understanding of context-independent things or properties

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[5] Whitehead's (1978/2010) views on biological processes are contextualized within a complex system of concepts offering a new process philosophy, hence they require a careful philosophical analysis before being used as a source. In other words, the main reason that Whitehead's claims are not directly discussed in this thesis is the extent of his work, which would divert my main focus away from the examination of biological processes. Still, I concede that this is a limitation of this thesis.

in isolation from relationality depends on decontextualizing them via operations of thought, i.e. making abstractions of actual cases that are always relational. Actuality is relational because contrary to an entity that is envisaged in an isolated state, a real entity exists within certain historical conditions (at a certain location and moment). When we make abstractions of historical conditions, we presuppose that the decontextualized entity can be re-contextualized within any possible surroundings. Ascribing certain absolute properties to an entity is derived from the experience of relations between the entity and the rest of the world. Can we say that being red is inherent in an apple? Assuming so would obviously mean disregarding the relational basis of colours in which a colour emerges in the context of certain background conditions, i.e. the principles of optics or the dynamics of visual perception are dependent on the relationing between the apple and the rest of the world. How should we interpret decontextualized entities or properties, then? Without a careful examination of the situation, we might not realize that there is a shift in the modality underlying any presupposition of isolated entities, which are mentally derived from actualities. The shift of modality is from relational necessity (actuality) to possibility for other relationalities. A property that is supposed as absolute is in fact a possibility that cannot be realized without alternative relationalities. Historical actualities are situations that have already been realized. By experiencing reality, we can derive knowledge concerning the inherent nature of things, but in fact inherent properties or isolated entities only denote possibilities concerning relational and processual confrontations. What we assume to be inherent is in fact a disposition for an event that can be potentially manifested due to fulfilment of certain conditions. For example, aside from the more complex organizational context of pigments that gives the apple skin its red colour, even the redness of a piece of iron oxide as a compound that has a simpler structure is context-dependent. A quantity of this compound exhibits red colour only if it is big enough for the emergence of colours, as colours do not exist without an assembly of molecules. Therefore, when we think of inherent properties or isolated entities, what we actually do is postulate that certain relational events are realized by a wide range of possible encounters between an individual and variations of surrounding conditions. In the supposition of a non-relational property, there is a potential confusion due to ignoring that the individual and surrounding conditions are subjectively distinguished. This is because an assumption of a non-relational property in fact disguises a fictional disassociation of a condition of relationality. We consider relational possibilities as dispositions due to individualizing an event (observation of red colour) and possible environmental conditions that ensure the manifestation of the event. However, we should not overlook that in this way of thinking, there is no ontological justification for prioritizing the individual object of this event, and doing so would lead to the misconception of absolute properties inherent in the object. Instead, what occurs in any actualization of relationality is an encounter of different causal backgrounds (either as individuated bodies, fields, flows with multiple components) having their own potentialities that can be manifested in different ways. In other words, an actual event is not a manifestation of a one-sided disposition, but a bi-directional (or multi-directional in cases of several components) synergetic confrontation that occurs as a case of relationing.

The abovementioned statement seemingly leads to a deadlock for the objective analysis of individuality. Considering that what appears as entities is the actualization of relationalities producing qualitative properties under different conditions, does it not follow from this that all there is left for individuality is a subjective identification? I believe that the answer is no, and that it is possible to reconstruct individuality on this relational and dynamic basis by focusing on the objective relation between self-organization and individuation. Individuation denotes the philosophical investigation concerning the basis of the individuality of things, which relates to issues such as identity, distinctness, unity, and haecceity, and which could be explained by appealing to spatiotemporal contiguity, matter, form, and so on. For instance, if the individuation of entities is claimed due to their matter, i.e. by asserting that individuality of an entity is due to being comprised of specific atoms without any replacement from the non-individual, then identity and form of many types of entities at higher levels of organization would be deemed temporary and fragile. This is because atoms become scattered and reconfigured on several occasions, and thus any rearrangement of atoms would lead to a disruption of the individuation that is based on a unity of specific atoms, even if the initial matter of the individual is replaced by new atoms. As an alternative, individuation can also be ascribed to the dynamicity of interactions. This alternative conceptualization prioritizes the identity of processes against the specificity of matter, and provides a more realistic description concerning the perpetuating nature of processes at higher levels. For example, an eye of a storm is not persistently composed of the same atoms in the course of the storm, yet we can still observe the eye from beginning until the end of this weather event. Only the process based individuation identifies and explains the actuality of this higher-level phenomenon. Collier (2004) provides an explanation associating individuation and self-organization on this basis. He points out that self-organization produces individuation, which is characterized by the cohesive unity of dynamical processes that provides the integrity of relevant systems (Collier, 2004, p. 165). Understanding this dynamic basis of individuation is essential for acknowledging the extended scope of self-organization that includes both living and non-living systems. More importantly, individuation of biological systems is exhaustively dynamic because of the constant circulation of matter between these systems and their environment.

Above, I discussed relationality and individuality in the context of actuality, whereas the more interesting implications of relationality lie in potentiality. Potentiality refers to causal capacities that have not been actualized, yet can be actualized upon stimulation, or due to the will of the agent as the source of potential. However, the ontological implications of potentiality are controversial. Potentiality is a mode of the non-actualized, and attributing potentiality to a real process (both in the sense of non-imagined and actual) seems problematic because this would mean that the actualized and the non-actualized co-exist within the conditions of individuality. Denying the ontic dimension of potentiality and acknowledging only logical possibilities (imaginations or actions of the subject) and flexibility of things (e.g. potential shapes that can be given to wax) in the context of potentiality might offer a solution by reducing potentiality to a common understanding of possibilities and dispositions. However, as I discuss below, potentiality has further implications, although the investigation of this ontological aspect of potentiality in contemporary philosophy pales in comparison with the literature on dispositions.

Aristotle's understanding of potentiality recognizes both the dimension of logical possibilities and the dimension of real powers that relate to motion and being. In Aristotle's view, potentiality does not correspond to a strict distinction between mind and matter, or pure actuality and pure potentiality, but it is a condition that determines the transformation of the form of the matter (Aygün, 2017). In this sense, the material cause offers potential that is to be actualized, but its actualization is due to natural motions including the agency of animals. In the sublunar world,[6] there is the intertwined existence of realized and unrealized potentials, decay and growth (Aygün, 2017, p. 44).[7] With the scientific revolution that was pioneered by Galileo and Newton, the Aristotelian distinction between actuality and potentiality was replaced by a mechanistic view that was restricted to the study of efficient causes. Modern attempts to revive the ontological conception of potentiality did not go beyond Whitehead's work on this aspect of causation in relation to process ontology (Bschir, 2016, p. 28). In a similar vein, Werner Heisenberg (1989) stated that quantum mechanics gives ontological potentiality a fundamental status, claiming that co-existent potentialities underlie a quantum state (p. 127). Yet, this kind of philosophical remark was not enough to fully recover the notion in contemporary scientific theories.[8]

In order to reconsider the theoretical option of real potentiality, it is necessary to replace the understanding that is restricted to the non-actualized with an understanding of a causal capacity as a condition of yet-to-be actualized. This latter condition can be realized in alternative conditions of individuality without itself being a precise preformation of any of these individualities. In other words, this type of potentiality is a possibility space without involving any specific individuated conditions. Gilbert Simondon's philosophical investigation of individuation is helpful

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[6] In Aristotelian cosmology, sublunar world refers to causal relations on Earth, which is imperfect, in contrast with the celestial revolutions that represent perfection.

[7] As will be explained in the fourth chapter, in Aristotle's view, the events in our world are finite but not random. The potential is about possibilities, and realization of possibilities requires both the materiality that is to be determined by external imposition and the formal cause that acts upon the material cause. When it comes to organism, materiality and formal cause are unified in the sense that the former is determined and the latter is determining.

[8] Some of the recent attempts aimed at rehabilitating the notion of potentiality in physics are discussed in Stapp (2009); Anderson (2011); Gabora, Scott, and Kauffman (2013); Cohen et al. (2013); and Eastman, Epperson, and Griffin (2016).

to acknowledge this potentiality aspect. Simondon (2004) criticizes distinguishing the principle of individuation from the actual individuation process itself, which he asserts to be evident in atomistic and hylomorphic philosophies (see Chapter 1 and Chapter 4 for the details of these approaches). In atomism, the principle of individuation lies in the infinity of atoms, and each atom's principle is its own existence. Thus, individuality is presumed before processes. In hylomorphism, the principle of individuation lies in the duality of matter and form, and temporality of the individuation process is explained by appealing to form that puts the matter into work. Thus, individuality is presumed to have formed after processes. Unlike these two approaches, Simondon (2004) asserts that an actual process of individuation is not separable from the principle of individuation. The approaches that only focus on the individual ignore the fact that individuation begins with pairing between the individual and its environment, in which the environment is far from being homogeneous and passive. He refers to the concept of *ontogenesis* to characterize the becoming of being. The notion of ontogenesis implies "being insofar as becoming", which reflects Simondon's process philosophy that takes into account the potentiality aspect. According to this, conservation of being occurs through becoming, which presumes a constant exchange between the structure and operation of systems (Simondon, 2004, p. 6). This is to be considered as a fundamental understanding of processuality: operation of systems is conserved – or solidified – as their structure, which in turn acts back on the ongoing operations. Furthermore, the notion of "being insofar as becoming" implies a perpetuated condition of potentiality. Simondon (2004) emphasizes that individuation is an operation of the complete being, which suggests a condition of unity. However, this does not mean that processes of individuation are devoid of internal dynamism. The individual relates to itself by sustaining the initial incompatibilities that are internal to the system, and the form is dynamically maintained before any final resolution of these internal tensions occurs. The potential of pre-individual reality is not consumed once and for all. In fact, consuming the potential for change corresponds to an equilibrium condition. The living system is in a metastable condition in which internal dynamism is maintained by the system's operations by utilizing its own potential. Thus, structuration of the living system is a new type of equilibrium vis-à-vis non-living systems for which equilibrium means the loss of potentiality. For living systems, metastable condition is characterized by the perpetuation of potentiality. The organism does not simply modify its relationing with the environment, which can be already done by the machines, but beyond that, it modifies itself "by inventing new internal structures and by completely introducing itself into the axiomatic of vital problems" (Simondon, 2004, p. 7).

Consider an embryonic stem cell. Is it a neuron-to-be, placental cell-to-be, or a bone cell-to-be? Obviously, none of them specifically, but all of them. The developmental path in which a stem cell differentiates into a specific body cell is an individuated process. Hence, what is observed through the differentiation process is an initial state of unshaped possibility, which involves possibilities for multiple end-states. Possibility turns into a certain state, and the capacity to differentiate into other types of cells is lost. This means that potentialities might arise and disappear depending on the situation. How should we interpret this type of dynamicity in potentiality? An interpretation of potentiality that is restricted only to dispositions underlines the fact that a certain capacity in an object[9] is manifested upon the fulfilment of certain external conditions. An ontological claim for potentiality does not need to exclude the aspect of dispositions, but it is dependent on further claims that extend beyond contemporary discussions of dispositions. Potentiality is an unprecedented condition within physicality; a condition that is not preformed within temporally deterministic cause-effect relations, but only externally demarcated by the influence of the external condition. Therefore, it refers to a limit of the spatiotemporal condition to shape the internal relationality. A localized actualization is antagonistic to a possibility space. It should be noted that this argument is not exactly same with a kind of indeterminism that can be presupposed from a single cause to multiple possible effects. The latter kind of indeterminism is still limited to postulating individuated causes and individuated effects. Instead, the view of potentiality that I propose involves indeterminacy due to the limits of penetration of the causal effect, and a questioning of the internal particularity of causal interactions. The unformed space has the potential for multiple ways of individuation. This ontological type of potentiality has profound

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[9] In an approach based on dispositions, it is claimed that potentialities are rooted in objects (Vetter, 2015, p. 3). I think this is controversial, but I will not go into a discussion of this issue here.

implications for part-whole relationships in a complex system of organization. Non-preformed potentiality space gives the whole a functional capacity to determine its own components depending on the requirements of the system in its relationing with the outer world. In other words, the whole determines its lower-level components. In the case of a self-organized system, the whole's viability and its interaction with the outer world are determining factors.

Potentiality is a physical capacity, but it is only utilized to a greater extent in biological processes, as only a self-organized living system can establish extensive internal functionality that is implemented through multiply realizable networks of organization. The idea that certain physical capacities are only actualized in living systems, and therefore we need to understand biology to be able to understand physics, was held by the pioneers of relational biology, namely, Robert Rosen and Howard Pattee. Rosen (1991, 2000) analysed living processes as transformations of relational wholes, and examined the formal cause acting on the initial conditions that are considered as the equivalent of the material cause.[10] In this sense, the attitude of relational biology is closely linked with a relational ontology, as the proponents of this view emphasize that the real implications of relationality can only be understood by examining living systems.

One might suggest that these fundamental claims concerning causation such as ontological potentiality should primarily be examined in relation to physics. However, research concerning the mechanistic understanding of non-living systems cannot be primary to a study of living systems, as the theory of living systems cannot be reduced to the theory of mechanical forces. I agree with the claim of relational biology that only the biological system involves a full realization of certain physical capacities. This is specifically relevant for relationality in biology, which is more complex in living systems due to the high degree of potentiality. I will not develop a detailed argument in favour of non-reductionism here, as this is not the main problem of this thesis. It is sufficient to state that even though one thinks that relationality can only be tested via physics, it is possible to find support for the

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[10] See Chapter 4 for a discussion of the Aristotelian basis of this way of thinking.

relationality view.[11] Relational quantum mechanics interprets the interactions at sub-atomic level by opposing the notion of an absolute event (Rovelli, 1996; Rovelli & Smerlak, 2007). According to this approach, properties of a system are determined merely in relation with another system. The first remarks foreshadowing this theoretical approach were made by Heisenberg, who stated that "the position of the electron is only determined in relation to a certain observer, or to a certain quantum reference system" (Rovelli & Laudisa, 2013). Relativity theory also provides support for this radical basis of relationality. According to special relativity, there is no absolute notion of simultaneity of events, as the simultaneity is decided due to the relation between two frames of reference.

This thesis puts forward a chain of arguments that combines ontological claims concerning relationality, processuality, and potentiality with an empirical and scientific examination of the organism in relation to subjects such as thermodynamics, nonlinear processes, pattern formation, and regulatory networks. A general claim that I defend is that self-organization of the organism provides a case for diachronic emergence. I will attempt to demonstrate the abovementioned claims concerning relationality by examining how the phenomenon of self-organization appears as a process of individuation. Self-organization is fundamental for the ontogeny of the organism, where the functional interdependence through part-whole relationships is manifested extensively. Yet, individuation dynamics are not restricted to the organism, as they appear in different ways due to far-from-equilibrium conditions of a system. The organism's self-organization is a special case in terms of canalizing the internal potentiality within a system. Components of the organism can be utilized in several ways due to the formation of higher-level entities, and functions can be implemented in multiple ways. In virtue of this special individuation condition, the self-maintaining capacity of the organism involves the idea of the organism as the sum of processes constantly utilizing its internal potential for change throughout its lifespan. In contrast, self-organization in a non-living system exhausts the potential of its far-from-equilibrium condition as the relevant process ends. Moreover,

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[11] More importantly, quantum mechanics supports the idea of potentiality (see above).

organizational hierarchy and regulative networks are characteristic to the organism’s organization. However, associating self-organization with both bottom-up emergence of order and relationality of the organism creates a conceptual ambiguity (Witherington, 2014). On this basis, I define the condition of the organism as regulative self-organization, whereas the formation of attractor states such as Benárd cells, reaction-diffusion systems, and oscillations, I define as transitional self-organization. This distinction is not completely new, as Pattee (2012) pointed out that organismic processes and spontaneous order constitute different aspects of self-organization. Pattee defines the organism’s self-organization as information-dependent. Since I prefer avoiding the philosophical controversies around the notion of information, I use the notion of regulation instead of information. Transitional self-organization defines the bottom-up emergence of order. Emergent order is incorporated within the regulative system of the organism through kinetic factors in bio-molecular processes and pattern formation in the development of the embryo. Within the organism, the underlying element of spontaneous order that arises in systems such as reaction-diffusion processes co-exists with genetic regulation, and therefore it is not possible to differentiate the contribution of transitional self-organization as an isolated element in biological processes. It is a misconception to suppose self-organization as inconsistent with organizational hierarchy. In transitional self-organization, bottom-up dynamics refer to the emergence of top-down control acting upon the system. Thus, the system’s transition to a correlated state is a hierarchical condition by definition. In regulative self-organization, bottom-up dynamics are coupled with top-down control of the organism in a more complex way. Centralized functions such as the operation of the immune system form the top of organizational hierarchy. The implementation of functions within the organizational hierarchy depends on centralized mechanisms using lower-level elements as a potential to realize certain goal-directed activities.

The development of my argument to this point has been based on a description of biological processes within the organism, and interpretation of them from the perspective of self-organization. This is preliminary to an examination of a more fundamental philosophical issue, which concerns the relation between self-organization and emergence. Self-organization is often mentioned in support of arguments for emergence. However, an understanding of the ontological condition of emergence requires an examination of its relation to potentiality. This issue also connects the organism's self-organization to the theory of relational ontology previously explained. Interrelations within the organism provide formal stability due to alternative organizational networks. This means that the parts of the organism can be utilized within the whole in alternative organizational networks. Therefore, in terms of both centralized functions and part-whole relationships, the organism as a whole can utilize its own parts as the potential for its metastable condition, as its viability can be ensured in multiple ways. Nonetheless, one could still argue that this way of understanding potentiality and emergence does not involve any inconsistency with the atomistic view that I criticized above. I explained that a perspective that restricts emergence to the arrangement of parts considers parts as static entities and reduces the emergence to an issue concerning the configurations of the parts. In other words, if the role of relationality and potentiality are excluded, then an emergent condition can be associated only with an actualized state. This kind of understanding reduces emergence to an empirical issue: nothing really emerges through a process because the output is already preceded in the input. Thus, in this understanding, emergence is epiphenomenal (Kim, 1996). On the other hand, an alternative consideration insists that emergence is real and diachronic (Mitchell, 2012), i.e. emergence is not preceded in a previous condition. Hence, the particularity of things is an end-state of the individuation process. The temporal basis of emergence depends on the unformed condition of the components when the dynamics of individuality acts upon itself. On this basis, proponents of epigenesis against preformationism emphasize that form is acquired through processes. The ontogeny of the organism exhibits incessant transformative processes from unshaped initial conditions to functionally formed self-production. This is not only restricted to the potentiality of stem cells, e.g. a folded biomolecule is also a potential that can be utilized in different forms at a higher level. In this sense, what we observe in ontogeny is the actualization of the dynamic form through the levels of organization and materialization of nonlinear processes.

At this point, we need to focus on the foundations of self-maintaining form. The form of the organism is like a boat that is constructed by its own passengers on a wavy sea.[12] Continuity of the form must face internal and external contingency elements. How is this possible? Dynamicity of the organism is coupled with the stabilization of the form. In this way, ontogeny is a process of constant change and relative formal stability at the same time. This condition is also related to diachronic emergence. In the organism, the synchronic condition is irreducibly diachronic. For instance, let us consider the form of the cell. The system spontaneously decays because of the entropy increase, which is why the parts of the membrane must be replaced constantly. Closure must also be sustained for maintaining the chemical processes of the cell. For any synchronic moment, we have a certain picture of the cell that appears as the form at that moment. However, considering processual actuality, the form in the synchronic condition is not possible without the underlying diachronic condition, which is the constant renewal of the parts of the cell. This situation is also relevant to the case of organism. In general, the organism's form is based on the cohesion of processes with different paces. Relatively stable elements of the organism also constrain more dynamic processes, such as the role of enzymes in catalyzing chemical activities (Moreno & Mossio, 2015). Through ontogeny, form is vitally dependent on the materialization of nonlinear dynamics, e.g. limit cycles appear as biological oscillators within the organism, which determine developmental rhythms, dynamic cell states, and circadian clocks. How should we understand diachronic emergence in these processes? I argue that the materialization of the processes is not reducible to a deterministic input-output relation because the synchronic condition at any moment is characterized by potentiality, that is, an unformed basis of individuation. This unformed basis does not correspond to any condition of actuality, as it only refers to a readiness situation that can be utilized by centralized functions. In other words, a diachronic process of stability that determines the synchronic condition cannot be considered as a sequence of consecutive moments in which there are particularized entities. The synchronic condition itself is a de facto condition that involves both a spatial limit for the further particularization of micro-level components, and a temporal limit

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[12] I borrow this metaphor from Otto Neurath (1944), who used it for the methodology of science.

for dividing the process into frozen moments including static entities. At a basic level, spatiotemporality is not individuated. For the organism, a complex situation of individuation is involved, due to the cohesions between fluctuations with different frequencies, changing and relatively unchanging elements, and short-term and long-term processes. This means that determination of the form in the organism is qualitatively different from the form of a non-living entity that lacks certain aspects of dynamism and potentiality. The organism is a self-organized process in which path-dependent constitution of materiality underlies its dynamic form. The actualization of the organism does not correspond to a strict material identity, but to a self-maintaining process based on the toleration of contingent elements that potentially endangers its viability.

I develop my arguments in four chapters. The first three chapters mostly discuss previous ideas relating to self-organization. In the last chapter, I develop my main argument concerning diachronic emergence in the light of the philosophical implications of relationality and potentiality. All chapters include certain sections that can be considered as the review of previous literature and historical developments of relevant ideas: theories that are developed based on the idea of self-organization are explained in the first chapter; the second chapter consists of a critical discussion of alternative theories, namely, autopoiesis and the theory of biological autonomy; I review the biological research that has contributed to the theory of self-organization in the third chapter; and finally, I examine philosophical arguments concerning the problem of emergence in the fourth chapter.

In the first chapter, I offer a distinction between regulative and transitional dynamics of self-organization. This is essential for my thesis, as it focuses on the connection between the emergent nature of the organism and a universal dimension of emergence as increasing complexity. In this sense, transitional dynamics describe the causal potential in multiplicity to become ordered, which is formulated by Ilya Prigogine’s account of far-from-equilibrium conditions. Regulative dynamics refer to self-organization in ontogeny, which is in line with the Kantian definition of self-organization that focuses on the reciprocal and self-producing nature of the organism. I also explain the thermodynamic basis of life’s organization, and in particular, Schrödinger's pioneering ideas concerning this issue, which involves a distinction between statistical laws and dynamic laws. Finally, I explain theories on autocatalytic sets, as autocatalytic sets are essential for exposing the intersection between regulative and transitional dynamics of self-organization.

In the second chapter, I discuss different views within the organizational approach, and explain why self-organization is preferable to alternative accounts. I also develop a brief summary of the early philosophical ideas relating to self-organization. I argue that self-organization is a universal tendency, and the organism's self-organization must be understood as a reflection of this general basis. In contrast with autopoiesis and the theory of biological autonomy (the autonomous perspective), only self-organization provides an interpretation for the connection between ontogeny and universal dynamics instead of developing a theory specific to biological processes.

In the third chapter, I describe the organism's self-organization due to a bi-directional interactivity between top-down and bottom-up dynamics. On this basis, I claim that it would be a misconception to think that organizational hierarchy and self-organization are inconsistent. On the contrary, self-organization concerns the emergence of hierarchy. Levels of organization are systematically involved in a dynamic form only in cases of regulative self-organization. In this sense, centralized function takes place at the top of organizational hierarchy. I explain how spontaneous order is utilized as an interlevel causation factor, and how immune system serves as a centralized function.

Finally, in the last chapter, I develop my main argument concerning self-organization. I argue that diachronic emergence is defendable in biological processes, as the synchronous condition of the organism is nothing but a de facto situation that sets a limit to diachronic particularity of causal relations. This is fundamental for acknowledging the emergent nature of the organism due to potentiality within internal relations, that is, relations determine the causal role of components. I adopt a view of relational ontology, and claim that nothing is exempt from relationality, hence organization. On this basis, I criticize the hylomorphic distinction between matter and form, as matter is itself nothing but an actualization of relationality at a lower level. I also examine the connection with different philosophical attitudes in biological research. Self-organization promotes the idea of organization at the organism level, which contributes to the critique of genetic reductionism. DST offers a similar criticism towards gene-centric explanation, and promotes the idea of self-organization. However, DST is not completely consistent with the approach of self-organization developed in this thesis, as it overemphasizes the role of contingency. Finally, I address the role of biological oscillation. Oscillators are essential in many aspects: they help to understand how processual dynamics are materialized through development, how nonlinear factors are incorporated in regulative self-organization, and how processes with different rhythms become cohesive in the organism.

I conclude this thesis by arguing that self-organization proves diachronic emergence. My conclusions concerning the potentiality of the organism, and the relational basis of ontogeny are more evident in comparison with my assumption concerning the limit of synchronicity. The latter includes more fundamental arguments concerning the nature of causation, which might seem to tend toward speculation. This is partially because this general assumption is indeed intuitive in certain aspects, hence it requires further philosophical investigation and scientific verification. Partially, this is because this thesis focuses on biological processes, and therefore it is not possible to explain these principles in relation to their broader implications.

Chapter One

Order, Disorder, and Self-Organization

Introduction

Systemic patterns or properties can arise through self-organization based on the reciprocal relations among the components of a system independent from any form of predetermination, templates, or external agents. According to this definition, any kind of endogenous dynamics leading to ordered structures can theoretically be attributed to self-organization, whereas a variety of questions would remain unanswered in this broad context: What is the self that becomes organized? Is a process of self-organization necessarily subject to individuality from the beginning, or is it characterized by a tendency for individuation? Or, is self-organization an objective quality, or is it a specific way of modelling systems?

The answers of these questions partly depend on what kind of phenomena is associated with self-organization. For instance, in the cases such as *order from noise,* self-organization refers to the emergence of an attractor state (Heylighen, 2001). This form of self-organization explains how a system explores alternative variations of its state-space until a new order arises due to the indeterminacy of the system (Heylighen, 2001). A similar phenomenon is *order through fluctuations,* which considers the amplification of fluctuations by creating a new order in dissipative structures (Nicolis & Prigogine, 1977). The focus of these studies is the synergetic relations within the system appearing in such a way that the relevant system ends up with fewer degrees of freedom (Bak, Tang, & Wiesenfeld, 1987). However, emergence of attractors is only a general way of defining self-organization, whereas not only an attractor state might appear in many different ways, but also self-organization is crucial for researching dynamics of complexity that are beyond attractors. For example, in biology, self-organization is mentioned for the group behaviour of social insects, or, in a Kantian manner, regulatory nature of the organism. Physicists mention concepts such as self-organized criticality in phase transitions, and chemists refer to the notion in relation with nonlinearity of reactions. Interdisciplinarity of the studies on self-organization creates the problem of potential inconsistencies between definitions as well as an opportunity for a multifaceted approach. As I will explain in this chapter, biological self-organization in particular cannot be separated from the theoretical implications of different fields such as thermodynamics, nonlinear dynamics, and chemistry. Therefore the diversity in using the concept is not a problem in principle, yet we must be cautious of the possible ambiguities that might arise. Using the concept in the context of an emerging pattern, a social insect colony, or an organism might create confusion as to the meaning of self-organization as well as conflation of different underlying dynamics.

I believe that a conceptual analysis of self-organization is necessary to deal with these ambiguities. The focus of research concerning self-organized systems can be broadly sub-divided into two categories: either the group dynamics which place emphasis on multiplicity, or the individual dynamics which regard a system as vitally dependent on the interdependency of its parts such as in the case of organism.[13] In either case, self-organization refers to the dynamics of individuation, which implies that becoming of the individual is an ontogenetic process before the individual, and not vice versa (Simondon, 2009). Gilbert Simondon's (2009) emphasis on the process nature of individuation is fundamental to the understanding of self-organization in this chapter, which implies the emerging condition of reciprocal relations within a system that enables it to act as a whole. Individuation appears as a tendency in many situations, and it is the degree of individuation that underlies the differentiating nature of self-organization between an ecosystem, colony, or organism. In biology, there is a wide spectrum of forms of individuation, which creates difficulties when assessing whether certain entities or processes are characterized by individuality such as in the case of holobionts or the quasi-multicellular form of the social amoeba. In this thesis, I will be examining the individuation dynamics of the organism, and the question of how we should

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[13] An understanding of the organism involves certain philosophical problems, some of which I will dwell on in my thesis in relation with self-organization. As I need certain postulates to begin with, I am not referring to any potential controversy at this point. Thus, here, the organism refers to an empirical consideration, typically, of a multicellular organism.

understand the self-organization dynamics in the ontogeny in relation to the universal implications of self-organization.

Self-organization is usually associated with the emergence of order, but how should we understand the increase of order? The second law of thermodynamics states that things go into decay, or in other words, there is a natural tendency for the increase of disorder. This is why living things have to be in a constant state of activity in order to “repair” their internal order. On the other hand, studies on nonlinear systems have demonstrated that self-sustaining order is not limited to living systems, and causal interdependencies arise in such a way that the local order of these systems increases. Hence, self-organization is a universal phenomenon that is manifest in both living and non-living systems, and life cannot be thought as independent from this nonlinearity basis. Organization creates patterns in which new constraints on the release of energy are introduced, which in turn leads to the more effective use of this energy, in Kauffman’s phrasing, by “extracting work” (Kauffman, 2000). This is a fundamental characteristic of the physical basis of life’s organization.

The abovementioned problems concerning the universal nature of self-organization demonstrates that the ontogeny should be considered from the perspectives of various disciplines engaging in related issues. In this chapter, I describe the scientific background of the problem. A conceptual analysis concerning self-organization is necessary due to the diverse approaches toward the notion in the literature. This will identify both the theme common to all these approaches and their differences. In some cases, self-organization is associated with the emergence of certain patterns, whereas in others, it is associated with the intradependent regulatory structure of the organism (Kant, 1790/2008; Goodwin, 2001). The implicit idea in the former is the emergence of order (Bak, Tang, & Wiesenfeld, 1987; Kauffman, 1993). In this case, interdependency is not a precondition, but it arises through processes. Thus, this type of self-organization is limited to the dynamics of a certain process. In the latter case, self-organization is understood in terms of the organism, which cannot be derived by appealing solely to spontaneous factors of order in nature, since downward determination from the whole is a necessary condition of individuality.

This chapter offers a distinction between regulative and transitional types of self-organization, which is a necessary preparation for the account of self-organization in ontogeny developed through this thesis. In transitional self-organization, the components of a system are not interdependent from the beginning, but they become so through a transformative process due to contingent effects within the internal interactions of the system. A typical case of transitional self-organization is a nonlinear process such as the formation of a vortex. In transitional processes, relatively uncorrelated interactors become correlated, which could create a novel condition of organization, whereas regulative self-organization is a condition of individuality that sustains its own activity. Regulative self-organization is exclusive to living systems,[14] while transitional self-organization can be observed both in living systems (e.g. social organization, ecological transformation) and non-living systems. However, regulative and transitional forms of self-organization don't have to realize as distinct from each other. On the contrary, these are quite intertwined dynamics in living systems, since transitional self-organization can appear at any level of biological processes from molecular interactions to macro-evolutionary dynamics. Organisms, as regulatory systems, are subject to macro-evolutionary transitions, hence to transitional dynamics through the evolution of populations. Furthermore, nonlinear dynamics at the molecular level, which are also transitional, are embodied within the organism.[15] The conceptual distinction that I offer in this chapter is preliminary to the ideas on the peculiarities of the organism's organization. By distinguishing dynamics of spontaneous order and regulation, which are both associated with self-organization in different ways, I aim to deal with the possible ambiguities with the concept. I also emphasize that the self-organization of the organism requires the spontaneous emergence of order, yet this alone is insufficient to explain the emergence of the self-organizing capacities specific to the organism.

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[14] Although self-organization (usually as guided self-organization) is also mentioned for artificial systems (Kernbach, 2008; Prokopenko, 2009; Nurzaman, Yu, Kim, & Iida, 2014), whose organization can be considered as regulative, machines are created by design, which is why their self-organized nature is controversial.

[15] As I will explain in more details in the following chapters, also nonlinear dynamics are incorporated in regulative self-organization.

1. Meaning of Self-organization From a Historical Perspective

Self-organization is a concept that is loosely defined. Its meaning varies between philosophical approaches and disciplines. Although the core ideas belonging to the concept are explicitly shared across the variety of perspectives, the scope of the phenomena considered as applicable to self-organization differs extensively. For example, self-organization can refer to the formation of organelles as described in cellular biology (Karsenti, 2008) as well as to the emergence of cosmological order interpreted in a Hegelian fashion (Jantsch, 1980). These differences also correspond to possible qualitative distinctions: does self-organization involve some type of agency determining its own principles, or is it simply the emergence of certain patterns; is there an objective criterion of orderliness implicit, or is self-organization merely a certain way of modelling systems (Gershenson & Heylighen, 2003)? In this section, I will try to answer the question of whether there is a common theoretical basis underlying these different interpretations by approaching this issue historically. This historical analysis will show that contemporary conceptions of self-organization are influenced by multiple disciplines including thermodynamics, nonlinear dynamics, cybernetics, and morphogenesis.

The problems of self-organization, complexity, and emergence go back to the Ancient Greek chaos-cosmos antagonism, which assumes that order in the universe has emerged by itself out of chaotic preconditions (Mainzer, 1993; Bushev, 1994; Heylighen, 2010). Chaos is the empty, unformed, and unorganized beginning of the universe, while the cosmos is a state of complex order. Chaos-cosmos antagonism originally had the mythical connotation in the ancient cosmogony, yet the ideas that are equivalent to modern theories of self-organization began when the supernatural agency was discarded as an explanation. Since an idea of a creator of organization is put forward as an external element, if this external agent is ruled out, then, a logical implication is that the emergence of organization in nature is a process in itself. In this sense, self-organization is a hypothesis that immediately appears with bringing the naturalistic explanation forward against the creationist myth.

This kind of reasoning appears in the ideas of Ancient Greek philosophers of nature. According to Anaximander, from the *apeiron*, which is the indefinite nature, regulated structures arise through cyclical changes such as the rotation of the heavens (Curd, 2016). This is an insightful idea from the contemporary viewpoint, since emergence of causal cycles out of chaos is a basic pattern of the self-organizing systems. Demokritos and Epicurus, who are the founders of two similar atomistic philosophies, claimed that all causal relations are nothing but the collision of atoms by chance. Epicurus in particular foreshadows the modern conception, as he contemplated that the random aggregation of particles leads to the formation of self-organized unities. According to Epicurus, atoms deviate from their course by chance while they fall, which is a phenomenon that is referred to as *clinamen* (Lucretius Carus, trans. 1994). On this basis, he considered that contingency has a key role in the appearance of organized relations, and embraced a non-deterministic worldview.

How relevant are these ideas in terms of the contemporary notion of self-organization? A modern equivalent of this ancient idea is a concept that is known as “spontaneous order”, “emergent order” (Holland, 2000), or “order from disorder” (Schrödinger, 1967/2013), implying that the order arises by itself. This is a phenomenon that is both local and universal. It is local because the organized patterns come into being here and there without the involvement of an omnipresent will or direct downward determination of a global power. It is universal because the local appearance of organized patterns here and there reflects a general tendency of the arising of systemic relations in nature.

One of the early usages of the concept in the modern literature was in Immanuel Kant’s *Critique of Judgement*. Kant claimed that the organism is self-organized because its parts exist only due to the whole’s functioning, which in turn depends on the interdependency between parts (Kant, 1790/1978). The organism is self-organized both as an individual, since it produces its parts, and as a species, since it reproduces.[16] According to Kant, the organism is a natural end, since it is both the cause and the effect of itself, unlike the artefact which is always

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[16] The differences between self-organization for Kant and contemporary accounts will be discussed in detail in the next chapter.

the product of an external designer. On the other hand, Kant was sceptical towards the randomness basis of order that has been promoted both in ancient atomism and evolutionary theory. Rather, his ideas on biological organization were influenced by the idea of *Bildungstrieb* (formative drive) that was embraced in the eighteenth century biology (Lenoir, 1980).

These ideas were formative to the development of the concept of universal evolution – not necessarily Darwinian, but as an organic transformation – that leads to complex, self-determining structures. This is evident in the idea of organic progress, which is formulated as the “transformation of the homogenous into the heterogeneous” (Spencer, 1891, p. 10). Herbert Spencer pointed out that this is an idea that has been developed by German thinkers such as Goethe, van Baer, and Wolff. He integrated this idea into Darwin’s evolutionary theory, and considered that all developmental processes, including the historical evolution of society, followed this organic law. Differentiation of a homogeneous body and arising of complex systems such as the division of labour in social insects and human societies increase the stability of the systems involved. Spencer’s organic law was precursor to self-organization in evolution and the related issue of the emergence of complexity, which I discuss further in the last chapter.

Another theory of this period that influenced contemporary ideas on self-organization was thermodynamics. With the discovery of the laws of thermodynamics in the nineteenth century, a conceptual distinction between chemical equilibrium and biological steady states had become possible. Due to understanding the principles of energy transformations, it was established that a perpetual motion that recycles its own energy source with full efficiency is not possible because a certain amount of energy is always wasted from the system as heat. Hence, the energy that can be used for work reduces in time. On this basis, Rudolf Clausius thought that, instead of energy, a new term is necessary to refer to a system’s incapacity to do work, which he called entropy, denoted with S. In reversible processes, entropy is measured by the exchanged heat divided by the temperature (Feistel & Ebeling, 2011, p. 20).

Ludwig Boltzmann developed the ideas based on this concept in statistical mechanics by introducing the notion of irreversibility in thermodynamic processes.

A main idea here is that a randomization will occur when two heterogeneous bodies come into contact. For example, when a hot gas and a cold gas are mixed, the temperature will spontaneously equalize between them. The molecules of the hot gas have higher velocity, so when a molecule with higher velocity and higher kinetic energy collides with a molecule that has lower velocity, the collision decreases the speed of the faster molecule, whereas it increases the speed of the slower molecule. In this way, the velocity of each molecule gradually approaches an average speed. The second law of thermodynamics identifies this process based on a ratio between a macrostate and the possible microstates that produce that macrostate. This is formulated as $S = k_B \log W$, where S is the entropy, k_B is the Boltzmann constant, and W is the number of microstates that are consistent with the given macrostate. A closed system evolves in such a way that the number of possible micro-configurations with certain macro-conditions of pressure, volume, and energy will either stay the same or increase. This corresponds to the increase of entropy. A Boltzmann analysis establishes that the gas molecules in a closed vessel will incline to the final state of macroscopic uniformity and microscopic disorder. In a closed vessel, gas molecules will diffuse from where they are highly concentrated to where they are less concentrated, thereby making the system more homogeneous. In the first state, the gas molecules are dense in one region, the molecules are squeezed in a smaller volume, and therefore there is a smaller number of possible micro-configurations. Whereas in the later state, the molecules are scattered, and there is a bigger set of alternative microstates that gives the same macrostate. The relevant randomization process is irreversible, and it is highly likely that the system will go into a more disordered state.

Organisms are also influenced by the increase of entropy, as they dissipate heat through their metabolic activities. After the late 1920's, chemists and biophysicists reconciled their views of chemical non-equilibrium and biological steady states (Keller, 2008), and the order in life was reinterpreted from the perspective of thermodynamics. It was revealed that the stability of life processes actually disguises underlying chemical instability. The macro-level stability of organisms is sustained because of the constant chemical activity that keeps the system in a far-from-equilibrium condition. Since chemical equilibrium means death for organisms, metabolic work needs to be constantly performed. Therefore, there must to be a constant flow of free energy into biological systems to maintain a state of chemical non-equilibrium.

This new thermodynamic understanding made it possible for a new concept of homeostasis to be introduced in order to discern biological stability from chemical equilibrium (Keller, 2009). Homeostasis refers to the active regulation of organisms that is necessary for maintaining stable conditions. Biological stability was already known before the chemical dynamics of biological order were revealed. However, with thermodynamics, it is now known that biological stability corresponds to chemical dynamism. The principles of order were first abstracted from its biological materiality, and biological stability was then re-contextualized in a more inclusive understanding of orderliness.[17] As I explain below, this paved the way for research into the role of non-equilibrium dynamics in life, which is a fundamental idea in self-organization.

From the 1940's and 1950's onwards, self-organization was discussed in the field of cybernetics as a concept which focused on controlling complex systems. Cybernetics emerged from the ambitions of developing machines with the inspiration derived from organisms. Thus, Wiener defined cybernetics as "the science of control and communications in the animal and the machine" (Wiener, 1961). The tension between the natural decay of systems and the evolution of living systems with a specific focus on the role of information, was a main issue that this approach addressed. Cybernetics is most-widely associated with the projects such as the design of a self-correcting weapon system, which was led by Norbert Wiener. Some of the other main ideas in cybernetics were concerned with understanding circular causality and feedback loops in biological regulation, and developing artificial intelligence on this basis. A main source of inspiration that drove cyberneticists to design controlled systems was the homeostasis of living systems. For example, Ross Ashby (1960/2013) focused on the activity of the brain as the basis of the organism's capacity for self-organization. His approach

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[17] On the other hand, equilibrium condition in thermodynamics does not include the kinetics of the system. As I will discuss in the third chapter, only a specific type of interactions that appear as kinetic factors can explain how dynamic instability instead of thermodynamically favoured stability occurs within living systems.

considers the brain as a performative device rather than a cognitive device that is engaged in representational activity (Pickering, 2009). The brain plays a crucial role in the organism's ability to adapt to its environment. It performs this function by randomly modifying the organism-environment interactions when this relationship is disturbed, so that a dynamic equilibrium between the organism and its environment is sustained in the face of new conditions.

On the other hand, Keller (2009) claims that the common narrative that refers to Kant and cybernetics as the pillars of the modern theory does not tell the whole story. The cybernetics project that was led by the U.S. Navy after the Second World War was abandoned by the early 1960's. This was also a time when the studies on nonlinear dynamics, which Keller claims to be the main theoretical source, have started to become appreciated in the Western world. Both in living and non-living systems, nonlinear characteristics of causal relations are a main theme in the emergence of order. The concept of nonlinearity refers to the uneven quantitative relation between the cause and the effect in an interaction, or between the inputs and the outputs in a system. More precisely, it suggests that a big effect might yield a relatively small change or a small incidence might create a big impact. This has a crucial role in part-whole dynamics because it marks the radical basis of context-dependency: the causal contributions of parts are finalized depending on their context in the whole system of interactions. Nonlinearity offers an explanation of systems as conflicting, dynamic, and open. The research on nonlinear dynamical systems has started with the Russian mathematician A. M. Lyapunov and has been a developing field in the Soviet Union from the early twentieth century. The introduction of this theory in control engineering was a significant source of influence that has triggered a long-term change in scientific culture and shaped today's understanding of self-organization. In control engineering, a main problem concerns stabilizing a certain output as a consequence of a certain input. Before the application of nonlinear approach, the output was considered as a linear function of the input, even though most of the real processes are nonlinear. When American scientists became aware of the studies on nonlinearity in an engineering conference held in Moscow, this area started flourishing in Western science, and the contemporary understanding of self-organization was developed on this basis (Keller, 2009).

Another essential moment in the development of research relating to self-organization in chemical reactions was Alan Turing's classical paper in 1952. Turing formulated a mathematical theory on the spontaneous appearance of patterns out of a homogeneous solution, which is known as the reaction-diffusion coupling (Turing, 1952; see Chapter 3). Turing's theoretical prediction that reaction-diffusion coupling could be a basis for biological structures has been validated by the observation that hexagonal, striped, and mixed patterns can be formed in chemical reactions from a uniform background (Ouyang & Swinney, 1991). The problem specific to biological systems is that this type of direct spontaneous order never appears as a sole factor of form. However, reaction-diffusion coupling has been proven to be relevant as a supporting factor in the morphogenesis of the embryo, e.g. in the formation of limbs in vertebrae skeleton (Newman & Müller, 2005).

A turning point in the development of the contemporary understanding of self-organization is the work of Ilya Prigogine on the dynamics of dissipative systems (Nicolis & Prigogine, 1977). The entropy production of systems has been explained above. Prigogine's approach points to another aspect of increasing entropy, according to which self-organization is defined as "an irreversible process, that is, a process away from thermodynamic equilibrium which through the cooperative effects of subsystems leads to higher complexity in spatial structures and temporal behaviour of the system as a whole" (Feistel & Ebeling, 2011). Self-organization appears in far-from-equilibrium conditions in which a constant flow is maintained due to energy input into the system. In an equilibrium system such as a crystal, the flow of free energy is minimized, whereas in far-from-equilibrium conditions, the system's fluidity is perturbed by a continuous application of an external force. The particles in this type of system respond to an external gradient in a way that they become correlated, creating heterogeneity. As a result, the system is trapped in a state where there is a constant flow of free energy into the system. Any relevant external force acts as a constraint on the system, after which the far-from-equilibrium system continues to become dynamic depending on its particular condition. Main examples of these systems are Bénard cells (see Section 2) and weather phenomena such as vortexes. A vortex is formed as a persistent motif of turbulence in the cloud patterns. Water molecules in the form of vapour are arranged in the cloud streets either moving upwards or downwards. Matter becomes condensed through the centre of the vortex, in which the swirling shape is formed. This type of self-organization appears as the reduction of the degrees of freedom within the system. In physics, Hermann Haken (2013) has developed his studies with a similar perspective, focusing on laser physics. In a laser device, a glass tube with mirrors at both ends is filled with molecules. Some of these molecules are excited by an electric current and become the control parameter, enslaving the individual molecules. As a result, coherent light emerges. The laser is considered a case of self-organization because the light wave within the device is not imposed from the outside, but arises through the reciprocal relations between the excited molecules. Haken coined the term *synergetics* as a synonym of self-organization, which was put forward as a new discipline, combining the theory of nonlinear dynamics, statistical physics, and Prigogine's approach to far-from-equilibrium systems.

Another research area based on similar problems is self-organized criticality, which refers to the idea that the nonlinear system can tune itself to tolerate the changes of parameters and still evolve into the same critical point (Bak et al., 1987).[18] The relevant studies began when Per Bak and his colleagues (1987) wrote a highly influential paper in statistical mechanics. The paper was addressing 1/f noise (also known as pink noise) that is ubiquitous in nature, which implies that the density of a frequency interval is inversely proportional to the frequency of the signals or fluctuating processes such as vacuum tubes, the flow of rivers, the heart rhythm, and the neural activity (Press, 1978; Bak et al. 1987; Nozaki, Mar, Grigg, & Collins, 1999). Simply put, the density and the frequency of a stochastic fluctuation in nature is expressed as a power law relation. Bak et al. (1987) claimed that 1/f noise can be explained by self-organized criticality. In this idea, the basic model is based on a rule of adding units into random tiles, which will slide into neighbouring tiles upon reaching a maximum. Small slides would be more frequent, and big slides would be more rare. In the long-term, the emerging pattern is an accumulating tension that approaches to a critical limit before a global chain of slides. This is explained by the metaphor of a sand pile. When the grains are

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[18] Self-organized criticality is a case of transitional self-organization (see Section 2.1 and 2.2).

dropped to accumulate in a pile, the grains that go on to the top of others slide to nearby locations by creating avalanches with different sizes depending on the slope. In this model, criticality basically implies that random inputs to a system lead to the transformation of this system until reaching a critical state. In this state, a small perturbation will trigger a big avalanche, and after this critical state is relaxed by a global slide, avalanches with different sizes will be repeated with a chaotic periodicity. This model is put forward as a representative of the 1/f noise, since a certain size of avalanche is found to be inversely proportional to its frequency.

In the following years, the idea of self-organized criticality has been applied to several phenomena including earthquakes, financial markets, and evolutionary biology. Sneppen, Bak, Flyvbjerg, and Jensen (1995) claimed that self-organized criticality can be conceptualized as a macro-evolutionary pattern that explains major catastrophes where the majority of species have gone extinct. In this model, they simulate the dynamics of an evolutionary system with randomly assigned barriers of change between species. The simulations assumed that random mutations that change the fitness of a certain species affect other interacting species either positively or negatively. Simulated evolution starts with uncorrelated species that have low fitness barriers, which means that a triggering effect of a random mutation in a neighbouring species would end up in a relatively small avalanche. It is found out that there will be local optima of the fitness value for each species. As species reach the local optima, they can survive without being forced by other species to evolve into a different species. As a result, randomly assigned barriers lead to convergent stable states for each species in which a species cannot evolve without a big chain of mutations. The pattern that emerged in the simulations reflects self-organized criticality: rare large avalanches of mutations lead to the rapid evolution of species through a domino effect between interacting species, since these avalanches rule out the convergent states for species in the previous conservative condition. Sneppen et al. (1993) claim that their model could explain sudden extinctions without necessarily presuming the involvement of externally imposed catastrophes such as the impact of an asteroid. They argue that a sudden extinction of species might occur because of a criticality state in the inter-species dynamics. Self-organized criticality is also suggested as an explanation of the underlying dynamics of punctuated equilibrium (Gould &

Eldredge, 1993), as punctuated equilibrium presupposes long periods of relative stability and occasional dramatic changes in the evolution of species (Bak & Sneppen, 1993; Sneppen et al. 1995).[19] Although hypothetical, this model serves as an example of how self-organization might be relevant to the emergence of certain patterns in the co-evolution of species.

In the 1980's, when complexity science and chaos theory were widely acknowledged as new fields, physics was the home of the studies on self-organization along with the studies on nonlinear chemical dynamics (Keller, 2009). Soon after, the ideas that originated in statistical physics found an interdisciplinary application, as the researchers started to investigate the implications of concepts such as complex adaptive systems. Later on, as the relevant literature diversified and became multi-disciplinary, the central role of physics has disappeared (Keller, 2009). The consequence of the shift from physics towards other disciplines has been a broadening of new areas of research considering biological systems as irreducible. Biological self-organization has become an independent topic in recent studies (Collier, 2004; Stewart, 2014), in which a systems approach has been emphasized. Social self-organization has been widely addressed under different topics as well, e.g. social evolution (Adams, 1988), antagonisms of modern society (Fuchs, 2004), the models of political behaviour (Galam, 2005), emergence of markets (Vriend, 1995), etc.

Kauffman's (1993) work is a paradigmatic example of how the ideas in statistical mechanics can be applied to other areas, as he did this for adaptive landscapes in evolutionary biology. He investigated self-organization by analysing several hypothetical conditions concerning the epistatic relations between genes. In his well-known work, *The Origins of Order* (1993), Kauffman specified this idea by investigating how some particular regulative combinations of genetic networks are expected to be effective depending on the degrees of intractability between genes. His work is mainly theoretical, but the relevant ideas have been applied to empirical cases in complex adaptive systems such as resilience mechanisms at

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[19] Frigg (2003) criticizes this model for being too simplistic in comparison with the complexity of real evolutionary process (p. 625), and for not providing any better explanation over other possible explanations for explaining 1/f noise.

molecular, organismic, and ecological levels (Desjardins, Barker, Lindo, Dieleman, & Dussault, 2015).

Beyond biological self-organization, Kauffman's theoretical approach is contextualized in a cosmological view. He states that "the universe might select its own laws and, somewhat like a biosphere, co-construct itself" (Kauffman, 2000, p. xi). The view of a co-evolving universe is based on the idea that law-like characteristics of systems are formed historically. Nature is complex, and complexity develops in ecosystem-like environments, having their own autonomous dynamics that are created within each system. Since the sub-systems evolve by constructing their own rules, this also calls into question the homogenous universality of the laws of nature (Mitchell, 2000). In a similar vein, theoretical physicist Lee Smolin discusses self-organization in this cosmological context. Smolin (2003) claims that we are living in a self-organized universe, and just as the biosphere on Earth is an evolving system by forming the laws that are characteristic of its internal structure, it might be the case that the universe has been expanding by constructing its laws in the intertwined subsystems. On this basis, he asserts that self-organization might explain fundamental characteristics of our universe. It has been calculated that the universe is old enough to have already reached thermal equilibrium. However, the actual increase of disorder is less than is expected to occur from the beginning of the universe. This is due to gravity, which counteracts the increasing entropy and dehomogenizes the systems by attraction. In this regard, gravity is the self-organizing force that is effective in infinite range and that keeps the universe from reaching thermal equilibrium (Smolin, 2003). This perspective is related to the role of self-organization in the universal emergence of complexity, which I discuss in the last chapter.

Contemporary understandings of self-organization mostly concern the transformation of a system with multiple components. For non-living systems, populations, or co-evolving species, the implicit idea is that specific patterns will appear in the transformation of the system due to endogenous factors. This basic idea is applied to model relationships in several disciplines. In life sciences, prey and predator relationships, slime mould aggregation, social insects, neural networks, and formation of macromolecules are some of the examples of a vast range of phenomena that are associated with self-organization. In addition to the natural sciences, self-organization is referred to in technological applications such as the working principles of lasers, or social sciences such as in the re-creation of society. Although there are some differences between these vast interdisciplinary applications of self-organization, they share a general emphasis on the idea of emergent order.

In biology, the most common application of the concept concerns the emergent properties of group-level behaviours instead of the organism level. In particular, self-organization is a pattern that is attributed to social insects such as honeybees, ants, and termites. Self-organization in sociobiological systems implies that organization is not established by a leader, blueprint, or well-defined instruction, but by rules of interactions that are “executed using only local information, without reference to the global pattern” (Camazine et al., 2003, p. 8). Complex structures such as termite nests are built by a large number of individuals, and the sophisticated group behaviour depends on the iteration of relatively simple rules of local interactions (Camazine, 2003). Typically, social insects are known to have complex systems for division of labour. Ants, for example, use pheromones to communicate with each other. Their trails bifurcate depending on stochastic elements, and experienced ants can lead others along these trails. They can also synchronize and alter the patterns of their foraging activities. In this kind of organization, the colony can discover alternative ways of regulating its collective activity, and tune its behaviour depending on the changes in the environmental conditions (Bonabeau, Theraulaz, Deneubourg, Aron, & Camazine, 1997). Self-organization in social insect colonies is so efficient at creating a tendency for individuality that these colonies are called superorganisms (Detrain & Deneubourg, 2006). As pointed out by Swenson (2010), this approach depends on “the collective behavior of already highly evolved multicellular organisms” (p. 167) instead of directly spontaneous order that is observed in non-living systems. This type of self-organization is a systemic property as a result of local interactions between agents that have limited information concerning the system. Although it is a case of multiple agents, the self-organized group acts as one, and the organization is not restricted to a single process, which is the case in transitional self-organization. In this regard, social insect self-organization exemplifies the regulative type just like an organism (see Section 2).

For example, the mechanism behind complex termite structures is the self-organization of the colony. African termites build large mounds as nests, which may reach 30 meters width and 6 meters height (Camazine, 2003). The mound is a castle for the colony: it includes walls for protection and acclimatizing the inner nest, a well-preserved chamber for the queen to lay her eggs, pillars to support the structure, channels for air circulation, and special combs to grow fungus. In the construction activity of termites, positive feedback mechanisms lead to the coordination of the activity, which also shows how random variations become an element of the organization. At the beginning, termites carry pellets independently, and randomly deposit them somewhere. Over time, pellets accumulate in certain places slightly more than others just by chance. As these small bumps of pellets act as a stimulus for termites, they start to deposit on these accumulations, and a self-reinforcing activity becomes prominent. Instead of a direct communication between individuals, the activity of termites becomes coordinated due to the information obtained from work in progress, which is a mechanism called *stigmergy* (Camazine, 2003). Stigmergy is a case of how the local interactions lead to a system's organization. Members of a social insect colony might also communicate via signals. For example, signals are used when ants of a colony scatter on the ground for foraging, and one of the ants finds a valuable food source such as a dead animal. In this case, the ant deposits a chemical trail as it travels back to nest, and the other ants follow this chemical trail.

Although self-organization appears extensively in the existence of complex systems of division of labour, group-level behaviour based on local interactions might arise with other species that have different degrees of complexity and hierarchy as well. This type of self-organization is observed with fish, birds, and primates. For example, fish schools evade predators by manoeuvring rapidly: splitting into two, expanding, or shifting direction. The group behaviour of the school is performed by the propagation of specific responses of a few individuals (Camazine, 2003, pp. 167-179). Geese fly in a V-shaped pattern so that the air resistance is minimized, and starling flocks constitute certain organized patterns when they fly (Mitchell, 2009). All these organization patterns emerge at the group level, and in general, feedback relations resulting in simple behavioural patterns are responsible for the emergence of group organization.

Self-organization of *Dictyostelium discoideum,* known as social amoebae, is one of the paradigm cases of biological self-organization. Conditions of emergent order are created by the social organization of the amoeba, and there is a controlled process of transition that constitutes a regulatory activity. Members of this species live as unicellular organisms, although they can also aggregate in order to form structures that behave as a multicellular organism. When there is enough food for all the cells, individual amoeba cells move in their substrates randomly. However, due to the population growth, the cells at the centre of the colony begin to starve, as they are not able to reach the food source. In response, these cells secrete a chemo-attractant known as cAMP (cyclic adenosine 3:5′ monophosphate). The waves of cAMP trigger a chemotactic cell movement, and cells form a temporal multicellular body, so that depending on the environmental signals, the colony gains new capacities to migrate, control the cell reproduction, or form a new colony (Weijer, 2005). Secretion of the chemo-attractant creates the patterns of streaming by positive feedback. Transition between these two states is a regulative activity, as the colony goes back to a non-organized state of the individual cells after the scarcity is dealt with.

As the abovementioned examples show, self-organization can refer to processes at the level of cosmological transformation as well as to certain pattern of local dynamics within a system. Hence, there is a vast diversity of self-organized processes. Even though emergent order and self-maintaining characteristics are common to all cases of self-organization, this diversity creates a problem for demarcating the boundaries or applicability of the concept of self-organization. As a result, in many cases, the underlying conditions that are associated with self-organization might be similar in certain aspects, yet the systemic context of emergent order might differentiate. For example, depending on the condition that self-organization is realized, the noise-driven aspect of the processes (Von Foerster, 2003), the emergence of heterogeneity depending on feedback relations (Newman & Frisch, 1979), the homeostatic control within the organism (Beer, 1984), or the bifurcations due to internal randomness (Prigogine & Stengers, 1984/2017) might be emphasized.

In order to develop a systematic approach to this diversity, several criteria have been suggested for classifying self-organized processes. One of these distinctions relates to whether there is a reduction in the degrees of freedom or not (Haken, 2013). In the example of lasers, certain control parameters enslave the rest of the system, which creates an attractor situation, whereas in some robotic systems of self-organization, the agents involved coordinate their activities without losing decision-making capacity. Hence, there is no reduction of the degrees of freedom within the system (Kernbach, 2008).

Another distinction relates to the difference between conservative and dissipative types of self-organization, which respectively refer to static and dynamic cases (Mainzer, 1993). Snow crystals are the products of the conservative type. The bifurcating solid structure of a snow crystal is self-organized in such a way that the system has low energy and the phase transition is reversible. In dissipative self-organization, however, the end product is an irreversible process with far-from-equilibrium conditions. A similar distinction is highlighted between self-organization and self-assembly. In the former, the system is a dissipative one, and therefore a constant energy input is necessary to keep the system in the non-equilibrium condition, whereas in the latter, the system approaches towards equilibrium (Halley & Winkler, 2008b). In thermodynamics, only self-assembly is a spontaneous process, as spontaneity refers to a tendency for equilibrium without any energy input. On the other hand, despite the fact that a process of self-organization requires an energy input, spontaneity is also mentioned in the context of self-organization. Here, spontaneous formation of patterns obviously does not refer to a negative change of free energy, but it refers to the fact that the process occurs by itself. In either case, the common basis of self-organization is a condition of individuation, in which reciprocal relations that are endogenous to the system are in place.

Another classification relates to living vs. non-living systems. For example, the case of self-organization in social insects (see above) obviously involves the manifestation of agency that is specific to organisms. It has been correctly emphasised that biological self-organization is not a simple reworking of the self-organization in the inanimate world, as the case is not simply replacing molecules with ants in the equations (Detrain & Deneubourg, 2006). Yet, this qualitative difference does not mean that self-organization is limited to non-living systems, or non-living and living types are distinct from each other in every aspect. Instead, it points to the fact that biological autonomy is a multifaceted problem that extends beyond self-organization. On this basis, it is suggested that living systems are self-maintained, but not self-organized (Moreno & Mossio, 2015). However, I argue that the way that Moreno and Mossio (2015) consider self-organization potentially overlooks the common themes between living and non-living systems, such as the role of far-from-equilibrium conditions and feedback relations that is observed in all types of self-organization (see Chapter 2).

Gershenson and Heylighen (2003) argue that self-organization does not refer to a type of systems, but to a specific way of modelling systems. This is because the relations that are studied in the context of self-organization are everywhere, and the observer decides where there is organization by ascribing purposefulness to the system. This claim is derived from the cyberneticists' argument that the criteria of order are determined subjectively. Indeed, Ashby (1962) proclaimed that "organization is partly in the eye of the beholder" (p. 258). He argued that the value of organization is determined by the functions with multiple variables, and the possibility space of organization is constrained by the communication between the parts of a system. Different observers might derive organizational possibilities from the actual set of components, and therefore the theory of organization deals with "properties that are not intrinsic but are relational between observer and thing" (Ashby, 1962, p. 258).[20] As I will show in the following chapters (see Chapter 2 for a discussion on autopoiesis, and Chapter 4 for a discussion on external vs. internal conditions of a system), this is a controversial claim, as it could lead us to misconstrue the criteria of organization as primarily subjective principles.

The notion of *self* signifies that the process occurs without any relation to an external source of design. A question that could be asked at this point is why self-organization, rather than merely organization? Principally, the notion of self suggests an endogenous condition, although the role of the relation between the system and its environment cannot be ignored. The answer to the question, above all, lies in the role of reciprocal relations within the system. Reciprocity between

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[20] According to Ashby (1962), there is no clear distinction between an observation by an observer that is also a part of the system and an observation from an external viewpoint. Despite this, Ashby expresses a preference for the former option, i.e. an attitude of second order cyberneticists claiming that as to organization, the systems are observed from within (see Chapter 2).

internal components creates a basis for self-sustaining processes. Therefore, any emerging condition of reciprocity is also potentially a transition from an uncorrelated state to an individuated state (Collier, 2004). As will be explained in the fourth chapter, whilst beginning of this transition might be contingent, it is the potentially self-sustaining character of relationality that enables the contingent establishment of the relation to become a basis of self-organization. This is why, for this type of processes, the relevant concept is self-organization rather than mere organization.

On the other hand, diversity of the concepts that are coined in this way, e.g. self-assembly, self-organization, and self-maintenance, indicates that several types of causal relations can be investigated due to the dynamics that are intrinsic and peculiar to the system. In general, if there is an organizing process, then this implies that the parts of a whole are arranged in a manner of utilizing energy to sustain specific relationality within the system. This brings cyclical causal processes into consideration (see Chapter 2), and due to causal cycles, the amount of work that is done through the cascades of energy release. In this context, self-organization can be considered as an umbrella term for investigating the ways that systems become work-efficient due to the interrelations. Yet, the details of how the work-efficiency is realized are essential: Does the process occur as a regulation or a transition? Is there reinforcement or inhibition with the causal relations? Or, is there an aggregation dehomogenizing the system or a dissolution? These differences point to a vast possibility area of diverse interactions.

In this section, I have discussed the variations in defining self-organization and explained the common theoretical basis across notions of self-organization. For instance, the notions of self-organized criticality in macroevolution, self-organization of a social insect colony, a self-organizing field as the morphogenetic development of an organism refer to very different phenomena. Still, they all are associated with the same concept and all share a common aspect, which is described as individuation (Collier, 2004). In the following section, I will explain what this common basis of individuation means, and continue my conceptual analysis by further exploring the distinction between transitional and regulative dynamics of self-organization that is consistent with these diversifying phenomena.

2. Transitional and Regulative Dynamics of Self-organization

In the previous section, I discussed various approaches to self-organization, and mentioned some of the classifications. Now, I consider another candidate for classifying self-organization. As mentioned above, the way that Prigogine defines self-organization denotes emerging order in far-from-equilibrium conditions due to the amplification of chance factors, whereas Kant defines self-organization based on the internal reciprocity of the organism. I believe that both of these approaches can be incorporated into a broader conception of self-organization as they correspond to different aspects of individuation dynamics. Self-organization due to far-from-equilibrium conditions is transitional, and it is widespread as a reflection of nonlinear causality, whereas self-organization of the organism – inclusive of, but beyond nonlinearity – is regulative. Therefore in this section, I offer a distinction between transitional and regulative types of self-organization. I also argue that there is still a common basis of these two types, which must be understood in connection with the role of spontaneous order. I begin by addressing Schrödinger's views on life, as his questioning is helpful to demarcate the problem of order in the context of thermodynamics, despite the drawback of preformationism implicit in it (Moss, 2003). Then I show how transitional and regulative dynamics correspond to different forms of self-organization, yet they are intertwined dynamics of biological processes. Finally, I discuss the role of autocatalytic sets, which are prevalent amongst explanations relating to the self-organized beginnings of life. Autocatalytic sets help to acknowledge the unified character of transitional and regulatory dynamics, since they set an example for the spontaneous emergence of bio-chemical regulation.

2.1 The question of life: *Order from order* or *order from disorder*?

In this section, I examine Schrödinger's approach to life's order and its critical treatments. The questions that Erwin Schrödinger (1967/2013) asked concerning the nature of life are highly important. Firstly, he approaches the question of life from two different understandings concerning its physical basis, namely, dynamical laws that are investigated at the micro level and statistical laws that appear as the properties of aggregated masses at the macro level. Secondly, he reflects on life as a phenomenon of order vis-à-vis entropy. He explains life as a case of *order from order,* as life depends on dynamical laws at the micro level instead of the statistical laws. Statistical laws are relevant due to macro-level properties that emerge as averaging effects out of micro-level disorder. However, emergence at the macro level due to self-organization is not involved in this relatively early theoretical approach towards life. This is pointed out by Moss (2003), who develops a critical account by emphasizing the far-from-equilibrium nature of organisms. Although Moss rightly criticizes the preformationist conception of Schrödinger, I argue that Schrödinger's phrasing of order from order can be made relevant to a modern theory of self-organization by replacing micro-level determination with organism-level regulation in the explanation. Lastly, I claim that a description of emergent order might have different aspects, which lays a basis for the distinction between transitional and regulative dynamics of self-organization.

In a book that deeply influenced relevant discussions in its aftermath, *What Is Life?,* Schrödinger developed a new understanding towards the question of life from the perspective of a physicist. Although many of his points are controversial and his general approach is criticized for being preformationist (Moss, 2003), his ideas have been a main source of inspiration in the theoretical developments in molecular biology, including the discovery of the double helix structure of DNA by James Watson and Francis Crick (Watson, 2001). Schrödinger identifies the antagonism between decay into disorder that is presumed by thermodynamics, and the order that is created by evolution.[21] As discussed in the previous section, the second law of thermodynamics entails an increase of entropy in closed systems. In living systems, however, this is not the case. Due to their metabolic functioning, organisms manage to reduce stochasticity by constantly exchanging materials with their environment. On this basis, he proposed the concept of negative entropy, which has found some applications in biological studies later (Jaffe & Hebling-Beraldo, 1993; Von Stockar & Liu, 1999; Jacob, Shapira, & Tauber, 2006).

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[21] This might seem relatively obvious today, but it was a novel idea back then. Another early remark concerning this antagonism has been made by the French philosopher Henri Bergson. As DiFrisco (2015) points out, although Bergson's approach to life was condemned due to its vitalist content, the philosopher's views were in fact in dialogue with the ideas in thermodynamics.

Schrödinger (1967/2013) remarks upon the randomness at the molecular level. The laws of nature apply on a statistical basis at the macro-scale, which means these laws denote approximate relationships that become relevant in so far as there is an aggregate of mass. For example, the margin of error in the calculation of macro-scale properties such as density, pressure, and temperature of a body of gas is inversely proportionate to the mass of gas. At the quantum level, leaps between different energy levels are stochastic. There is a higher probability of a leap to a higher energy state when heat is applied to the system, but there is no deterministic limit in terms of a change of the energy state for each particle. The ordered relations are observed only in a large multitude of particles, and physical interactions diverge from certain expectations as the size of these interactions decrease.

Life overcomes the stochasticity of the micro level, which led Schrödinger (1967/2013) to investigate the basis of molecular order in living systems. He hypothesized that genes must be aperiodic crystals. Similar to the atoms of a crystal, which are microscopically ordered in a periodic arrangement, living systems are molecularly ordered. Yet, their microscopic arrangement is hypothesised to be aperiodic because genes are considered as heterogeneous bodies that are small but sufficiently large to both keep their structure intact and constitute the higher-level order by coding the components of life. In other words, structural patterns are thought to constitute the living system due to deterministic dynamics at the micro level.[22] Contrary to statistical laws that apply at the macro-scale, the source of orderliness against the decay due to heat is dynamical laws that are relevant for the micro-scale. On this basis, Schrödinger presupposes a clockwork type of determination from the micro level to the macro level.

Moss (2003) criticizes this understanding of biological order for being preformationist, as the source of order is considered to be in the heritable material. Schrödinger's hypothesis on life depends on the idea of the gene as a coding-script, which presumes that genes include all the information that is necessary to construct higher-level properties of the organism. The notion of *order from order*

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[22] Although the molecular structure of genes had not been revealed then, the idea of hereditary code-script was promoted by Schrödinger (Moss, 2003, p. 54).

implies that the micro-scale order determines the macro-scale. Moss (2003) claims that this approach is based on a naïve conception that the cell is “a disorganized bag of atoms” hence “... the need for a solid-state aperiodic crystal to serve as that bedrock of order” (p. 56),[23] disregarding the basic claim of self-organization that the order arises from disorder. This leads to ignoring the organizational aspect of life, which involves the role of intercellular interactions and the role of membrane compartmentalization in keeping the system far-from-equilibrium. Cellular membrane system is the basis of non-equilibrium condition of the organism. A complex system of tagging the biomolecules and molecular signalling enables their passage through the membranes according to functionally appropriate contexts by utilizing physical processes such as diffusion. Glycoproteins are modified due to differentiating enzyme activity in nested compartments. Variations of the oligosaccharide chains are provided by adding or removing a certain sugar unit, or by chain branching of the molecules (Moss, 2003, p. 86). Depending on the variability of glycoproteins, several types of membranes are reproduced. In this continuous production of cellular membranes, the processes of self-templating and complex feedback loops are essential. In this regard, Moss (2003) highlights the regulatory nature of the living systems, which keeps their heterogeneity at the organism level, as an alternative to Schrödinger’s claim depending on the hereditary code-script as the only executer of order. What Moss (2003) discusses is a complex network of compartmentalization in a multicellular organism as a basis of far-from-equilibrium condition. Of course, the relevant regulative dynamics at the molecular level were mostly unknown when Schrödinger developed his ideas, as Moss points out. Thus, Moss’ criticism targets not only Schrödinger’s ideas, but also focuses on the persisting idea of gene-centric interpretation of life’s order that is inspired by Schrödinger’s discourse. In this regard, the emphasis on the regulatory nature of life by Moss provides a basis for a contemporary understanding of biological self-organization. His critical stance draws from recent scientific developments that offer a more detailed explanation of the organizational

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[23] Moss’ (2003) main criticism is that this preformationist conception conflates the Mendelian gene that is based phenotypic expression and the molecular gene, although the notion of gene as a coding script has failed. I will discuss the criticism of genetic reductionism in more detail in the fourth chapter.

aspect of biological systems. Schrödinger could not have known about these developments or the critical arguments against his view that followed. Still, despite these drawbacks, Schrödinger's book on life was in the vanguard of progress on the issue due to pointing out the thermodynamic basis of life, and describing metabolic activity as a non-equilibrium condition.

Goodwin (1987) is another critique of gene-centric preformationism and a proponent of self-organization. Similar to Moss (2003), Goodwin (1987) criticizes the view that gene as the part can determine the whole, yet he contends that the organism is a phenomenon of order from order, albeit from a different perspective from Schrödinger's. He claims that there is a downward determination from the whole to the part, and the organism is a self-organizing field. Morphogenetic transformation of the fertilized egg is a main example of this self-organization. Cleavage patterns in the division of cells are determined geometrically by the developmental constraints imposed by the whole. According to this approach,

> Heterogeneity ("parts") arises as a result of systematic transformations of the organized whole, which may be described as the manifestation of states selected from a potential set that satisfies a primary property of invariance characteristic of organisms. Thus, the organism is not so much a self-organizing system that generates an ordered state from disordered or less ordered parts; it is more a self-organized entity that can undergo transformations preserving this state. (Goodwin, 1987, pp. 170-171)

As mentioned above, both Moss (2003) and Goodwin (1987) are critical to the idea of the gene as the code-script that is represented by Schrödinger, and emphasize the holistic aspect of the organism's organization. In this sense, the difference in the ways of describing self-organization, that is, *order from disorder* in Moss' account (sure enough, as a reference to Prigogine's ideas), and *order from order* in Goodwin's account, does not necessarily point to a disagreement on the main characteristics of life's organization. These authors do not deny the corresponding ideas that are implicit in the alternative uses of the concept: Both non-equilibrium dynamics, which is implicit in the idea of order from disorder, and downward determination that is geometrically imposed, which is implicit in the idea of order from order, are acknowledged within the mentioned approaches in different ways (see Chapter 3 and Chapter 4).

Why does self-organization seem to be associated with different patterns, then? I believe that the distinction between transitional vs. regulative dynamics of self-organization underlies the prima facie conflict between *order from order* and *order from disorder*. Moss (2003) mentions self-organization in the context of spontaneous order that also plays a role in living systems, whereas what Goodwin (1987) points out is a type of downward determination in which the regulatory aspect of the system is prominent. Therefore, an ambiguity in the concept of self-organization is due to a conflation between regulative and transitional dynamics that leads to this prima facie difference. In the Kantian approach to the organism, the reciprocity between the parts and the whole is emphasized. The self-organized character of life as discussed by Kant mainly, but not exclusively, concerns how the order is sustained. This type of self-organization pays specific attention to the interdependent relations between the parts of a whole. In a processual respect as well, the organism's organization is understood as a case of order from order, since the development and metabolic activities of the organism are maintained as a downward determination through its lifespan. In the case of an organism, the whole is regulated by itself, but obviously the organism itself is not the initiator of this organization. Unlike the self-organization of a flame, life does not arise spontaneously, but it regulates itself (Haldane, 1949), and therefore the organism's organization is mainly regulative. In contrast, in the case of far-from-equilibrium conditions such as Bénard cells (see below), the system is uncorrelated at the beginning, and the interdependency is established through the process. In this context, it should be referred to as transitional self-organization. In the following section, I will try to delineate this conceptual distinction.

2.2 A conceptual distinction

Self-organization is due to a process of individuation both in living and non-living processes as a consequence of the emergent interdependency between components. In processes that are referred to as order from disorder, which implies the spontaneous emergence of certain patterns in non-equilibrium conditions, self-organization is the very process of the formation of interdependency. In the case of the organism's self-organization, we do not see the becoming of organization from an uncorrelated phase, but there is an incessant regulative activity of the organization. This interdependency is a given, as the system must be organized from the beginning. On this basis, in this section, I offer a distinction between transitional and regulative dynamics of self-organization. In transitional self-organization, reciprocal relations between the components drive the transformation of the system into a state where the parameters of the system drastically change and a new order arises. Whereas the organism's self-organization is regulative, and its main characteristic is a constant responsiveness to any perturbations that can disrupt its structure. Nevertheless, this distinction does not mean that the organism's regulation is detached from non-equilibrium dynamics, since biological stability of the organism includes underlying far-from-equilibrium conditions. The emphasis on the regulatory character of the organism's self-organization exposes the need for a further condition of individuality in addition to the spontaneous dynamics of order.

First, let me explain why self-organization is due to a general condition of individuation, which forms the common basis of the processual nature of living and non-living systems. As Collier (2004) states, "the fundamental problem of individuation is to understand how parts of a thing can be parts of the same thing" (p. 155). There are different ways of answering this problem, e.g. appealing to the possession of a common essence or spatiotemporal contiguity. Instead, Collier (2004) goes on to claim that the unity relation, which he calls *cohesion,* is the underlying reason of the individuation of systems (p. 155). Cohesion denotes the processual basis of relations that enables the system to maintain its integrity against internal and external fluctuations (Collier, 2004, p. 165). Self-organization creates the condition of cohesion, hence the individuation (p. 169). In a similar vein, the French philosopher Gilbert Simondon (2009) puts forward the principle of individuation as opposed to the conception of atomism, which considers the individuality as a given, and hylomorphism, which presupposes the aspects of form and matter as distinct from each other. Atomism considers individuals as given, already solidifying the principle of individuation, and thus individuality at higher levels is ascribed to chance events in which atoms are reconfigured. Hylomorphism assumes that form is the basis of individuation. Considering dynamic processes which produce individuality, this corresponds to focusing on the end-state of individuation instead of the becoming of individuality, which is the individual that is on the edge of the individuation process. Simondon expresses his alternative view as follows:

> There is ... the presupposition of the existence of a temporal succession: first there is the principle of individuation, then this principle undertakes an operation of individuation, and finally the constituted individual appears. If, on the contrary, one supposes that individuation does not only produce the individual, one would not attempt to pass quickly through the stage of individuation in order arrive at the final reality that is the individual--one would attempt to grasp the ontogenesis in the entire progression of its reality, and *to know the individual through the individuation, rather than the individuation through the individual.* (Simondon, 2009, p. 5)

Individuation is a relative condition because the potentiality for new conditions of individuation is never completely exhausted. Therefore, there is a constant pre-individual state of individuals that can be realized through new relations. For the living individuals in particular, Simondon (2009) emphasizes a metastable state that enables living things to modify themselves “by inventing new internal structures and by completely introducing itself into the axiomatic of vital problems” (p. 7). This implies that stability is not given at any condition, but it is temporarily acquired through multiple processes that produce cohesive structures. Furthermore, individuals participate in greater individuation of collective unities, and thereby dimensions of individuation are formed step by step through the magnitudes of scale (Simondon, 2009, p. 9).

As a consequence of individuation, the principle of organization is not predefined, but it is established due to *epigenesis* (see Chapter 4). The individual cannot precede the process of individuation, but on the contrary, individuation is the source of the particularity of an individual (Simondon, 2009). It is this basis for individuation that characterizes the universal aspect of self-organization, and therefore there is no reason to think that self-organization in ontogeny is isolated from broader individuation dynamics in other relational conditions emerging in living systems. Transitional and regulative dynamics are both defined within self-organization, since they refer to different aspect of individuation dynamics. Becoming of individuality is mainly a bottom-up process, which is realized through a process of epigenesis within a system as a given, or towards the constitution of new systemic interrelations. This offers an explanation why self-organization is also usually associated with bottom-up factors. In both types of organization that have been discussed, bottom-up factors are involved in certain ways, as the local interactions create an integrated whole at a higher level. In self-organized systems, in fact bottom-up and top-down dynamics are coupled in a way that the local dynamics (bottom-up) lead to a systemic individuality. In transitional self-organization, when the convenient conditions exist, such as an external gradient, bottom-up dynamics would lead to a correlated state, as analysed by dynamical systems theory. Interdependent systems, whether they become self-organized or they are already self-organized, gain a certain degree of capacity for regulating their parts, which means that top-down dynamics dominate (in the case of transition) the initial process of emergence. In non-living systems of self-organization, this regulative capacity is minimal and temporary, and limited to the spontaneous dynamics of order, whereas in biological individuals, regulative self-organization behaves as a long-term unification of processes of exploiting and controlling the bottom-up dynamics of spontaneous order. Contrary to a single diachronic case of emergence, in the case of regulative self-organization, there is a complex system of potentiality which is characterized by the levels of organization.[24]

Now that I have described the general frame of self-organization due to a tendency for individuation, let us look at the role of non-equilibrium dynamics more closely, which is the basis of processes that I referred to as transitional self-organization. In far-from-equilibrium systems, there is an emergent order as a result of a transformation that changes the conditions of systemic relations. The macrostate of a far-from-equilibrium system is dynamic, as it does not have a solid structure like crystals. Bénard cells are regarded as an exemplar of far-from-equilibrium conditions due to self-organization (Keller, 2009; Swenson, 2013). These cells occur when a liquid is heated from below. The heat acts as a constraint triggering the pattern formation (see *Figure 1.1*). In the initial state where there is no temperature difference, molecules move in various directions randomly. As an effect of heating from below, a temperature difference occurs, causing a density

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[24] At this point, the notion of biological autonomy (Moreno & Mossio, 2015) is necessary to understand the mechanisms of multiple self-constraints reducing the stochasticity of the organism systematically (see Chapter 2 and Chapter 4).

gradient. Due to this, the molecules move upwards from the bottom layer where the fluid becomes less dense. After a critical threshold is crossed, whereby upward movement of the molecules becomes faster than the average random movement, the molecules overcome viscosity and begin rotating either clockwise or counter-clockwise. Then, these rotations become correlated with each other by forming convection cells in different sizes. Many cells are formed at the beginning, and the smaller cells are subsumed by the bigger ones throughout the process. As a result, emerging macroscopic currents constitute the hexagonally shaped Bénard cells (Swenson, 2013).

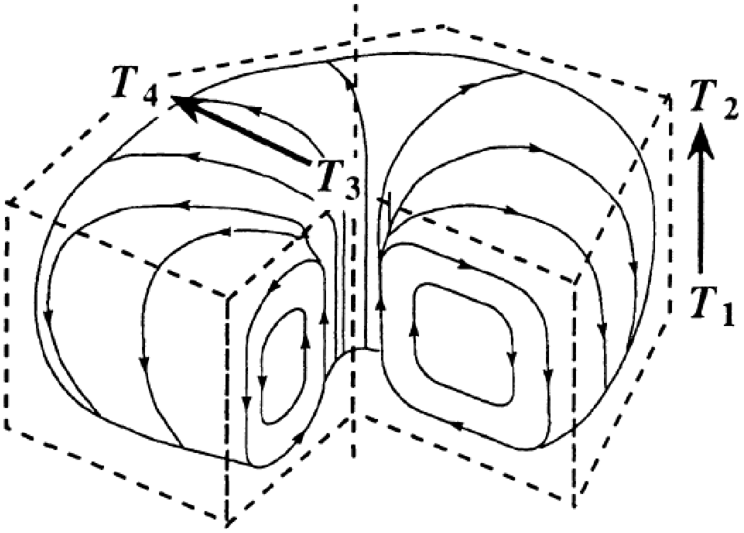

Figure 1.1 Bénard cells. $T_1 \longrightarrow T_2$ shows the heat gradient that leads to upward movement, and $T_3 \longrightarrow T_4$ shows the increasing surface tension caused by the movement of heated molecules (from Swenson, 2013, p. 168).

The formation of Bénard cells is an example of a far-from-equilibrium condition through energy flow, which shows how spontaneous order emerges. This situation does not contradict the general increase of entropy. The heated fluid is an open system. When Bénard cells are formed, heat still dissipates out of the system and contributes to an overall increase in entropy. Yet, through the process that leads to Bénard cells, there is an opposite tendency within the system, the emergence of self-organized shapes. Of course, the order due to transitional self-organization does not reverse the more inclusive increase of disorder, but it appears along with the increasing entropy. This occurs by the local emergence of self-organizing relations in which energy is used to sustain the temporary boundary of the system.

As shown in the example of Bénard cells, self-sustaining loops arise through the flow due to a constraint that enables overcoming the random dissipation of energy. This creates the bedding of nested systemic relations, as the emerging internal localities of order are maintained by exploiting the rest of the system. This process is caused by self-maintaining cycles appearing within the system under suitable conditions. The stability of the self-organized system is based on a viability principle by definition: The randomness of a system is accompanied by diversity of several interactive ways, and among them, the forms of interaction which became more efficient to enforce and maintain a specific order would be more likely to sustain themselves. This aspect of self-organization is the emergence of an attractor state, which can appear not only in non-living systems such as hurricanes and convection cells, but also in biological systems such as the organization of social systems and noise-driven evolutionary dynamics. Therefore, this type of self-organization is a fundamental physical capacity. It is a pattern that arises whenever there is a multiplicity of components under suitable conditions.

As a structural pattern, transitional self-organization is a transformation from an uncorrelated state to a correlated state by utilizing the internal randomness of the system. Two factors are necessary for the transformation to a correlated state: first, a sudden or gradual change in the surrounding conditions that becomes a constraint, and second, locality acting as bottom-up dynamics, which determines the system’s reaction as a self-constraint. Locality of interactions is due to the internal randomness creating a causal asymmetry within the system (Hemelrijk et al., 2005). In other words, locality implies the causal effect of contingency that contributes to systemic changes in a nonlinear way. Through the processes of transition, even though it is known that amplified locality will somehow affect the system’s pathway, it is not possible to predict precisely which contingent factors will end up in systemic changes and what exact path will be taken. The amplified asymmetry in local interactions is always engaged in a higher-level correlation that is finalized in the organization of the whole, that is, asymmetries due to micro-level contingency become opportunities for a novel condition of coherence condition at the systemic level. The appearance of these coherent structures in the macro-conditions is well acknowledged in the literature on the emergence of complexity due to internal dynamics. Feedback loops have a key role in this kind of transformation. In a system with high complexity, positive feedbacks lead to macro-state asymmetries by enabling the amplification of random elements, which creates subsystems acting semi-autonomously. The consequence for the sub-systems is an increase of energy efficiency, as sub-systemic loops can drain energy from the rest of the global system. Or, these sub-systems can be arranged in ways that can drain the potential of the externalized parts, which also corresponds to harnessing the usage of energy at the systemic level. The general consequence is that the same amount of energy can create more complexity if harnessed through several mechanisms, as is well known from metabolic activities.

Several authors remarked that the abovementioned processes imply a global tendency to maximize complex order and production of entropy at the same time (Nicolis & Prigogine, 1977; Juretić & Županović, 2003; Salthe, 2004), and some of these authors have also suggested that this global tendency should be formulated as a fourth law of thermodynamics (Morel & Fleck, 2006; Swenson, 1989, 1991, 2009). Swenson (1989) put forward this as the law of maximizing entropy production. To define this process, he termed the notion of *autocatakinesis*:

> An autocatakinetic system is a system that maintains its “self” as an entity constituted by, and empirically traceable to, a set of nonlinear (circularly causal) relations through the dissipation or breakdown of field (or environmental) potentials (or resources) in the continuous coordinated motion of its components. (Swenson, 1991, p. 50)

With the notion of autocatakinesis, Swenson (1991) refers to individuation dynamics, or more specifically, a natural tendency for individuation in complex systems. Thus, he argues that in autocatakinetic systems, the law of maximum entropy production applies. This law (or mentioned as a principle in certain studies) presumes that complex systems tend to maximize their internal production of entropy (Levine & Tribus, 1978; Lorenz & Kleidon, 2005). It is stated as: “A system will select the path or assembly of paths out of available paths that minimizes the potential or maximizes the entropy at the fastest rate given the constraints” (Swenson, 2010, p. 173). The idea under this notion has been discussed in physics and the physical basis of living systems since the 1970’s. Furthermore, it has been claimed that this principle can show a connection between thermodynamics and cognitive autonomy (Wissner-Gross & Freer, 2013). The law of maximal entropy production is also connected to self-organized criticality (Dewar, 2005), although this claim has been disputed (Grinstein & Linsker, 2007). In general, this principle remains a controversial question in physics (Prokopenko, Ay, & Polani, 2013, p. 6). Swenson's approach suggests that the scope of cases that can be explained in terms of transitional self-organization might be much larger than originally conceived. However, to formulate a new law out of this type of self-organization is significantly more ambitious. I return to this issue in the following chapter. Below, I focus on the other side of this debate, and will argue that transitional dynamics of self-organization might have dissimilar consequences in different complex systems despite the generality of the phenomenon.

To explore these differences, let us compare two different cases of transitional self-organization: Bénard cells, which are generally regarded as the paradigm case for non-living self-organization, and an experiment concerning the role of contingency in the self-organized evolution of bacteria populations (Swenson, Arendt, & Wilson, 2000). In the process of the amplification of contingent factors with Bénard cells (as the molecular movements are swept through emerging loops), it is not possible to precisely predict of the specific transformation of the system at the micro level – albeit one could also argue that this is due to an epistemic limitation – whereas it is possible to predict the macro-state of the correlated condition that appears as the hexagonic cells. Therefore, the formation of Bénard cells is not an open-ended process in terms of creating a condition that is latent with other qualitative transformations, i.e. geometrical formations other than the hexagonic shape is not expected. On the other hand, in the case of bacteria colonies, the role of amplified contingency is different. In parallel evolution experiments with quite identical bacteria colonies, it has been demonstrated that, due to sampling errors, noise can lead to dramatic differences in the evolutionary path between separate microcosms including ecosystem properties such as the acidic level of the environment (Swenson et al., 2000, see below). This means that contingent factors can lead to divergent paths of evolution in which bacteria colonies survive in different ways. It is known that microorganisms always evolve in interdependent ways in symbiotic networks such as biofilms, where multiple species develop symbiotic networks. This also implies a potential for immense diversity due to alternative symbiotic combinations, which is why a slight difference in the beginning condition can create a different end-state. The amplified contingency provides alternative options of viability in different populations, and an emergent self-organization determines the specific evolutionary path. In this regard, it is asserted that self-organization creates a new dimension in the parameter space of ecosystem dynamics (Wilson, 2005, pp. 160-164). Different from Bénard cells which are not predictable at the specific arrangement of the microstate, but only predictable due to the form of their end-state, the self-organized characteristic of biological evolution has progressive consequences. Arguably, this is because biological systems are capable of creating more organizational hierarchy and higher levels of interdependent complexity. Moreover, this demonstrates that transitional self-organization has far-reaching implications in biological systems.

The abovementioned cases should be understood in terms of bottom-up dynamics in transitional self-organization by the amplification of contingency. On the other hand, regulative self-organization occurs in living systems in which top-down dynamics are dominant and perturbations are tolerated. This kind of organization is also a matter of interplay between bottom-up and top-down dynamics, as the parts and the whole determine each other reciprocally. A multicellular organism is an ideal example of regulative self-organization with restrictive top-down mechanisms in several important aspects: Regulatory feedback has an extensive and fundamental role from cellular activities to homeostatic mechanisms; gene-editing mechanisms reduce the possibly negative effects caused by copying error; the immune system destroys the cancerous cells emerging from mutations, and regulates the microbiota in the body by tolerating neutral and beneficial microorganisms and killing possibly harmful ones, etc. In addition, there are centralized functions such as the one of the nervous system in which external stimuli are coupled with the actions of the organism. In this sense, regulative self-organization of the multicellular organism is a case of high-level interdependency. It is claimed by different authors that self-organization dynamics enable the formation of intradependent structures, which are favoured by evolutionary selection (Kauffman, 1993; Batten, Salthe, & Boschetti, 2008; Mitchell, 2012). On the other hand, this aspect of self-organization is only possible through the regulative basis of organization, which spreads through the reproduction of organisms. In other words, reciprocity between the parts is sealed by the regulative whole. The origin of the regulative self-organization in a cell is the division of another cell, and as to an organism, it is the reproduction of parent organisms. In this sense, life is the continuity of this regulative type of order that has persisted on Earth for billions of years, as this maintenance of biological organization can be understood as a long chain of life cycles. In this regard, albeit not in the exact way that Schrödinger defined, the main pattern in life is *order from order,* typically in an organism, since for regulative self-organization, the main pattern is the maintenance of order within individuality.

In summary, self-organization can be defined as a bottom-up emergence of systemic relations building the system's own top-down dynamics. In transitional self-organization, the bottom-up emergence of systemic relations is prominent, whereas in regulative self-organization, the constant activity of top-down dynamics determines the individuality of the system. Organisms are characterized by functional integrity, and their functional integrity is based on constant regulatory activity such as the replication of genes, production of enzymes, homeostatic mechanisms, etc. In homeostatic mechanisms, the intradependency of the self-organized system is already established at the beginning of the process, and the downward determination of the biological processes has a vital function for individuation. Therefore, self-organization does not refer to a single transition, but to a regulatory control due to feedback relations. In this sense, regulatory organization contextualises the phenotypic outcome as a consequence of the interconnectivities between the components of the system. This occurs due to metabolism, physiology, and gene regulation (Jaeger & Monk, 2014). For example, in metabolic activities, feedback processes determine body's sugar consumption and storage. Cells break down sugar, which generates the end product of ATP (adenosine triphosphate), and the accumulation of ATP leads to a negative feedback, which inhibits the enzyme activity producing ATP. Various similar processes depending on feedbacks are responsible for the self-maintenance of the organism through homeostatic regulation.

Nonlinear dynamics of order are incorporated within the regulative basis of organization. Consider the role of the dynamic instability of the microtubules in the organism. These are the organelles made of tubulin proteins, dynamically shortening or lengthening within the cell, thereby controlling cellular activities such as division, transportation of biomolecules, and so on. The dynamic shape of these organelles is due to a nonlinear process in which hydrolisation of GTP (guanosine triphosphate) into GDP (guanosine diphosphate) leads to the shortening of the one end of the tubular structure, or GDP's reassembling into GTP leads to lengthening that end of the organelle. In this way, the organelle can move within the cell, or its size can change. Dynamic instability in this example acts as a bottom-up factor in the organization of the whole organism. This means that the dynamics of the process are not directly controlled by a centralized structure, but their occurrence as a bottom-up factor contributes to biological functions at higher levels such as cell division. As another example, the role of stigmergy in the organization of a social insect colony, which I mentioned in the previous section, can be considered in the context of the bottom-up constitution of order due to local interrelations, since the organization at the colony level is due to local rules of interactions.[25] Bottom-up factors of this kind are only one aspect of the overall self-organization because maintenance of the system depends on the downward determination from the whole. As the organism as a whole is a regulatory system, part-to-part relationships are bottom-up factors, and the part-to-whole relationship, in line with Kant's definition, is both determined due to, and for the sake of, the whole. However, when we consider the role of bottom-up factors in a case of transitional self-organization such as the formation of Bénard cells, we see that bottom-up factors lead to an emergent pattern that is peculiar to the process, and the emergent properties that are created by the local interactions are temporary, as the systemic correlation ends when the process is over. Both in transitional and regulative types, random variations have a role in the emergence of organization, yet with an important difference, bottom-up factors in the case of spontaneous

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[25] I stated that regulative self-organization appears in the organisms. Social insect colonies are complex regulatory systems, and therefore, the appearance of this type of self-organization supports the claim that they are superorganisms.

order are not utilized in higher-level functions and they are not constantly regulated.

The distinction between transitional and regulative dynamics means neither that the regulation of an established order is the sole mechanism in living systems, nor that the emergence of order is exclusive to non-living systems. In the emergence of order, the multiplicity of the components in a system is a key factor. This is evident in cases such as Bénard cells where the emergent order relates to components that become interdependent. This is a physical capacity, and there is no reason to think that life is exempt from it. In fact, emergent order is exploited and encapsulated by the regulatory mechanisms of life. This is due the fact that self-organization gives an adaptive capacity to the organism, which is improved once it becomes the target of natural selection (Mitchell, 2012). Life exploits the causal capacity of self-organization, at the biochemical level in particular, as it builds on nonlinear processes that can maintain themselves. At the micro level, formation of patterns has a crucial role, which appears in cases such as noise-induced phenomena, morphogenesis, or spontaneous self-assembly (see Chapter 3). This also explains a basic difference of living systems and self-organized processes from aggregates of particles that spend time in possible micro-configurations evenly, as the former deviate from homogeneity and change in an irreversible way.

As transition and regulation refer to structural aspects of processes, the distinction within self-organization is relevant as an abstraction, whereas in actual systems, we see nested systemic relations in which these dynamics are intertwined. There is a reciprocal relation between these two types of dynamics. Emergent order might lead to the creation of regulatory structures as well as physical dynamics of transitional self-organization can be exploited by life as an element of functional integration. Dynamics of emergent order have a role both at the micro level due to emerging patterns embodied within the autonomous system of the organism, and at the macro level due to transitional self-organization appearing through the co-evolution of ecosystems. Moreover, the organism itself represents the unification of regulative and nonlinear dynamics, as I explained before that organism's metabolic activities create a far-from-equilibrium condition. Reflections of transitional dynamics can also be found in the developmental processes. Jaeger and Monk (2014) argue that regulatory robustness of organisms can be explained due to a way of genotype-phenotype mapping that is similar to the attractor basins of dynamical systems. An attractor basin is a sub-region of a phase space to which the parameters of a trajectory converge. Due to the regulatory nature of the genetic networks that buffer the perturbations of some of the mutations, different genotypes might have similar expressions at the phenotypic level. Two different genotypes that are almost same with each other might correspond to different robust states when they are expressed in the phenotype, hence these genotypes would be involved in different attractor basins. This approach emphasizes the role of nonlinearity at the intersection of evolutionary dynamics and ontogeny.

The reciprocal relation between transitional and regulative self-organization can shed light to theories about the beginning of life. One of the main hypotheses concerning the origin of life is the emergence of autocatalytic sets that led to the formation of first RNA (see Section 2.3). It is argued that spontaneous emergence of these autocatalytic sets from inanimate matter points to the role of chemical self-organization (Vasas, Fernando, Santos, Kauffman, & Szathmáry, 2012), which indicates that transitional self-organization has historically played a role in the evolution of organisms as regulatory systems. The Sun is the main source of free

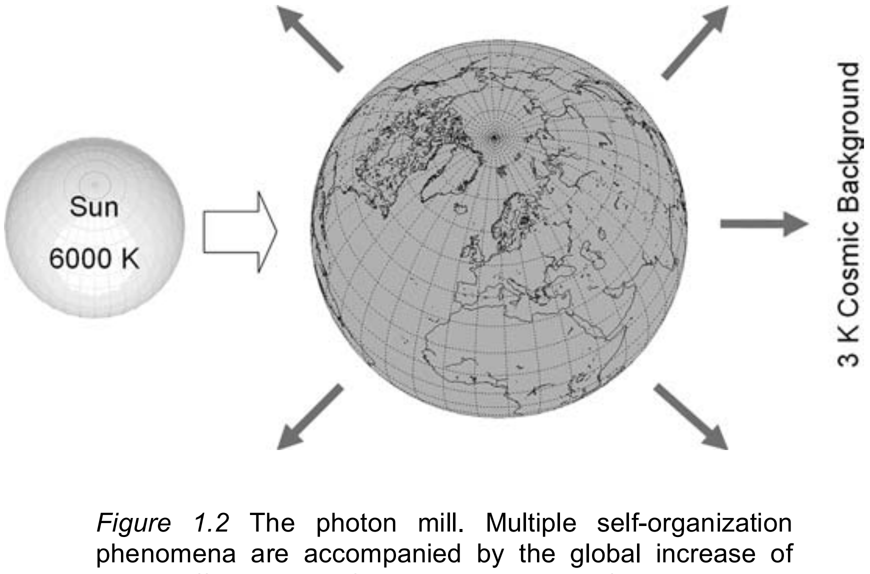

Figure 1.2 The photon mill. Multiple self-organization phenomena are accompanied by the global increase of entropy (from Feistel & Ebeling, 2011, p. 89).

energy on Earth. As a result of a continuous flow of photons from the Sun to the Earth, entropy is produced proportionate to the thermal gradient between temperature of the hot Sun surface (6000 Kelvin) and cold outer space (3 Kelvin). The amount of entropy production also corresponds to an upper limit to the ecological self-organization on Earth, as living systems depend on utilizing solar energy (Feistel & Ebeling, 2011, p. 90). From a cosmological viewpoint, there is a local increase of order on Earth because light energy is captured by the process of photosynthesis, turned into chemical energy, and harnessed through the metabolic activities. Since living systems are characterized by negative entropy, at a global scale, the biosphere corresponds to a far-from-equilibrium condition utilizing solar energy as an external source.

The entire chain of processes in which light energy is fixed by autotrophs, turned into chemical energy, and then used for the metabolic activities of heterotrophs is a case of transitional self-organization, as the global increase of order on Earth corresponds to a local increase of order in the universe. However, the relation between self-organization and evolution is not limited to this global condition. Studies such as *Nk model* (Kauffman, 1993) and the application of self-organized criticality to evolution, which I explained in the previous section, involve the idea of transitional self-organization that also appears in research into adaptive landscapes. An adaptive landscape is a way of modelling that represents the fitness of differentiating genotypes, which includes peaks of high fitness and valleys of low fitness. Valleys and peaks correspond to fluctuations of polymorphism within the population. Valleys are areas of low fitness, in which polymorphism increases due to lower selection pressure, while it decreases in peaks of high fitness. Typically, a peak in the adaptive landscape is followed by a valley due to the expected fluctuations of polymorphism within the population. This is expected when mating within the population is random. However, it is found that in some cases specific phenotypes equally represent the peak, and the periodic appearance of valleys is skipped (Wilson, 2005). This implies that a subset of genotypes have adapted in a way that their fitness is maximised collectively, for all these genotypes occupy the adaptive peaks due to genetic recombination. In a radically epistatic system, even if the inbreeding within the population is random, a subset of genotypes with a higher fitness rate can be generated randomly in the phenotypes as a consequence of an inbreeding subset of genotypes (Wilson, 2005). The epistatic subset consists of intermediate forms in which genotypic characteristics arise together. Due to interdependent expression, relevant genes collectively survive through this evolutionary process, which sweeps the expected decrease in the fitness level, and leads to consecutive peaks in the adaptive landscape. The interdependency between genes is expressed in the phenotype, and genetically intermediate forms might not be phenotypically intermediate. This exemplifies an emergent pattern in evolution as a consequence of reciprocal relations established within the system.

There is strong evidential support in favour of the dynamic relation between natural selection and self-organized patterns emerging at the ecological level. Dynamics of self-organization can affect evolution in different ways: by the neutral mechanism of random drift, by suppressing selection pressure, or by facilitating natural selection (Wilson, 2005). This effect usually occurs through noise-driven processes, in which contingent effects and the reciprocity of relations lead to the evolutionary pathways that are influenced by self-organization. Emergence of interdependency at multiple levels of selection is a basic condition of this reciprocity in evolution, which has been observed in different experiments. In one experiment, forty replicate yeast populations were isolated and observed for several generations (Lang et al., 2013). It was found that different point mutations were fixed across the populations, and in certain cases neutral mutations were more likely to survive than the adaptive ones. This was because these mutations arose in cohort-like structures in which interdependent genes were passed on together. Moreover, this reciprocal effect might appear as a nonlinear phenomenon by leading to an emergent type of order within an ecosystem. This was shown in another experiment, in which almost identical microcosms were formed by inoculating microbes from a common source (Swenson et al., 2000). This experiment found out that the evolution of these microcosms was sensitively dependent on the initial conditions, as the small deviations could be amplified by the interrelations within the system. Initial variations due to noise effect, which were regarded as small differences between the systems that were negligible, led to dramatic divergence between evolutionary pathways after several generations. Separated microcosms evolved in such divergent ways that properties at the level of the ecosystem such as the suitable pH level of the environment and degradation of toxic materials differed between systems. This demonstrated that heritable differences in reciprocal interactions between organisms were responsible for the noise-driven evolution (Swenson et al., 2000).

It should be clear that the emergent patterns in the evolution of ecosystems are obviously transitional. On the other hand, since evolving populations in the abovementioned examples are comprised of organisms, which are regulatory systems, this means that regulatory systems are the sub-elements of transitional self-organization. Vice versa is also true: transitional dynamics at the molecular level are embodied within the regulatory body of the organism (see Chapter 3). The second aspect is usually discussed as part of the physico-chemical basis of life. As will be explained in the following chapters, a relevant approach states that the dynamics of self-organization are transformed into the multicellular organism due to the moulding of natural selection (Newman & Bhat, 2009). Spontaneous emergence of higher-level patterns depending on local interactions and far-from-equilibrium dynamics appear in several biological processes with different scales. Dynamic instability of the microtubules, dynamical states of the cells such as oscillatory behaviour that are passed on to divided cells, and the role of self-organized fluctuations in morphogen gradients are some examples of these utilized transitional dynamics within the regulatory system (see Chapter 4).

In this section, I discussed transitional and regulative aspects of self-organization. I also claimed that these are unified within the organism, and intertwined in living processes in general. With this conceptual clarification, I considered possible confusions relating to self-organization that arise from a conflation between spontaneous dynamics of order and self-maintaining nature of living systems. The intersection of these two types of dynamics points to the emergence of autocatalytic sets back in the history of life. Therefore, in the following section, I examine how autocatalytic sets offer an explanation for the evolutionary basis of regulative self-organization.

2.3 Autocatalytic sets

Autocatalytic sets, which are collectively catalysing chemical reactions, are widely debated due to their role in the origin of life (Hordijk, 2013). They make it possible to extend evolutionary pathways to molecular selection, as chemical self-organization was a main drive of evolution before the appearance of genetic inheritance mechanisms. In this section, I discuss autocatalytic sets as an origin of regulative systems that appeared as a consequence of transitional self-organization in which bottom-up dynamics are dominant. The scientific models and empirical findings discussed below indicate the high probability that the first biological systems emerged as a result of spontaneously formed self-sustaining loops. Hypercycle (Eigen & Schuster, 1977) is one of the first models of self-organization in this context (see Chapter 2). I focus on the work-constraint cycles (Kauffman, 1993), and RAF models (Hordijk, 2013), which have developed from the ideas related to work-constraint cycles. These models are essential for self-organization as they are attempts to explain life's order in the face of entropy. Kauffman (2000) argues that the simplest form of life should consist of a work cycle that is able to overcome the increase of disorder. In this view, the basic unit of biological autonomy is a work cycle that consists of the coupling of a spontaneous and a nonspontaneous reaction. However, although life generally depends on this type of coupling, the claim that a simple work cycle can be a minimal condition of biological order is controversial. Thus, I will examine a recent revision to this account, which considers autocatalytic sets to include some additional elements as the nutrient source of the system (Gatti, Hordijk, & Kauffman, 2017). I argue that this revision also indicates that the emergence of life's regulatory structure cannot be sufficiently explained without also considering the implications of an ecological transformation, which is an issue that I discuss further in the following chapter. Furthermore, the question of how spontaneous order contributed to the origin of life remains to be controversial, as there are different theories concerning the origin of life. This question also relates to the debates concerning the minimum chemical conditions for life, e.g., whether membrane closure is necessary for life or RNA based catalysis came first. Under any circumstance concerning these alternative hypotheses, the chemical decay due to thermodynamic stability and life's kinetic solution to this decay is fundamental, which demonstrates the significance of self-organization in understanding the origins of life.

Eigen's hypercycle is one of the first studies on the autocatalytic nature of early life. Formation and degradation are combined in organisms (Eigen & Schuster, 1977, p. 547), and therefore biological systems must produce themselves continuously. In this context, Eigen worked on the notion of hypercycle in which several self-maintaining cycles are connected with each other, proposing one of the first models of self-organization based on autocatalytic sets (see Chapter 2). Later, Kauffman (1993, 2000) proposed a similar model, which was applied in experimental studies and other mathematical theories, sometimes with modifications (Hordijk, 2013). According to this model, a simple autocatalytic set includes two polymers, namely, polymer *A* and polymer *B*. Each of the polymers is constituted by two sub-fragments: *A'* and *A"* are the sub-fragments of the polymer *A,* whereas *B'* and *B"* are the sub-fragments of *B*. There is a reciprocal relation of catalysing between *A* and *B*, as *A* catalyses the binding of *B'* and *B"* in order to make *B,* and likewise, *B* catalyses the binding of *A'* and *A"* in order to make *A* (see *Figure 1.3*)*.* In this way, it is supposed that the entire production of the components of the system is to be catalysed collectively (Kauffman, 2000, pp. 31-32).

Kauffman's (2000) theory is essential because he proposed that spontaneous dynamics of self-organization and life's regulation are not distinct phenomena. He claims that the minimal unit of biological autonomy is a work cycle that couples spontaneous and nonspontaneous reactions. In metabolic activities, exergonic

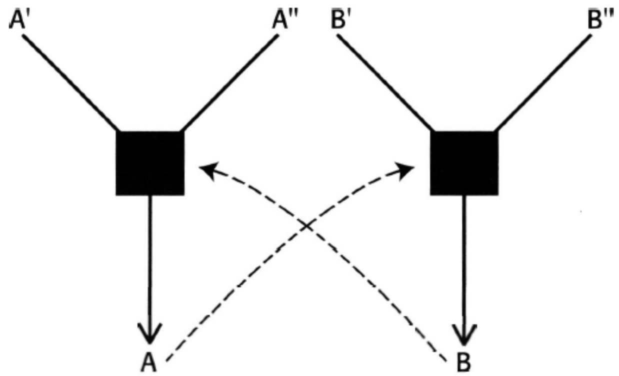

Figure 1.3 Kauffman's model of autocatalytic sets. Black squares represent the reaction of ligation of the Polymer *A* and Polymer *B.* The arrows show the reciprocal relation of catalysis between a ligated polymer and the sub-fragments of the other group (from Kauffman, 2000, p. 32).

reactions are spontaneous, which implies that free energy is released after these reactions, whereas endergonic reactions require an input of energy, which is stored in chemical bonds. The coupling of these two reactions implies that the release of free energy from an exergonic reaction is used to fuel the endergonic reaction by forming a self-sustaining chemical activity. Experiments have not verified the appearance of the work-constraint cycles without other regulatory mechanisms (Kauffman, 2000). However, as will be shown below, some modified versions of this model have been supported by empirical evidence.

One of Kauffman's (1986) early ideas on autocatalytic sets, named the binary polymer model, predicts that in an environment with different chemical reactions, randomly established relations between products catalysing other products would transform into a set of collectively catalysing chemical reactions. Kauffman also presumed a probabilistic calculation, according to which he concluded that the emergence of autocatalytic sets would be inevitable at some point. Kauffman's argument concerning the inevitability of autocatalytic sets was criticized for supposing a constant logarithmic increase of catalysis of the molecules, which is unrealistic for the actual conditions, and for not recognising the evolvability of the system (Lifson, 1997; Vasas et al. 2010; as cited in Hordijk, 2013, p. 878). Still, this initial model on autocatalytic sets was developed further in other studies. One type of models is called RAF (reflexively autocatalytic and food generated) sets (Hordijk, 2013). In this model, one set is defined for the types of molecules, whereas another set is defined for the types of chemical reactions. Also, available types of food in the environment are defined as a subset of molecule types. Finally, a catalysis set is defined in which specific reactions catalyse specific molecules. Accordingly, in a situation where all reactions are catalysed by at least one catalyst and all the molecules are produced from a food source, the system is an autocatalytic set (Hordijk, 2013, p. 878). In RAF theory, the original representation of the autocatalytic network in which catalysts are also the products is modified, as the new model defines them separately. It is emphasized that the RAF model can include the factors for evolvability (Hordijk, Steel, & Kauffman, 2012), and it has found a wider application (Gatti et al., 2017). This mathematical representation indicates that, similar to Eigen's hypercycle, a hierarchy in the organization of autocatalytic sets might appear through evolution. The conjecture is that the autocatalytic process alternates between different subsets, and smaller autocatalytic cycles are nested in or intertwined with more inclusive cycles. This kind of alternation and nonlinear development of autocatalysis also implies competition and selection between subsets (Vasas et al., 2012; Hordijk, 2013; Hordijk et al., 2012). Also, intertwined RAF sets are more robust to perturbations than selfish RNA molecules (Hordijk, 2013, p. 880).

It is beyond doubt that the existence of life in its current regulatory forms would not be possible without catalysis. Enzymes, which maintain the kinetic conditions of a reaction that would otherwise thermodynamically occur in a much longer time, are the most essential catalysts. A crucial question with autocatalytic cycles relates to the capacity for self-sufficiency, more broadly, to a possible concern directed toward the “self” in theories of self-organization. Current life forms depend on a complex network of reciprocal self-production that includes enzymes, nucleic acids, and so on. It is found difficult to model a self-sufficient biological system that is simpler than this complex organismic condition because even though RNA and DNA molecules are self-instructive, none of these parts are able to replicate without the organizing whole. To overcome this problem, in vitro experiments are designed to create viable cycles of chemical reactions that could represent more simplistic equivalents of today’s complex networks of life. These experiments show that this kind of chemical cycles can in fact be created artificially (Hordijk, 2013, 877). More recent studies focus on the evolvability, emergence, and robustness aspects of the problem that requires understanding possible self-driven mechanisms enabling the increase of complexity.

Autocatalysis has crucial implications in terms of the emergence of order in biological processes through nonlinear effects. In chemical equilibrium, there is a causal cycle between the reactants and the products in a way that the rate of the forward reaction that produces the products and the rate of the reverse reaction that produces the reactants equal each other. In autocatalytic reactions, however, the causal cycle is nonlinear, as one of the products of the reaction also acts as a catalyser of the reaction. The chemical reaction has more than one fixed point in autocatalytic systems, as it is fixed as a function of the concentration of the reactant that is also produced. This kind of loop also has multiple macro-states and, therefore, it is more ordered than a reaction which does not have autocatalytic characteristics. As mentioned in the first section, according to entropy formula, a system is more ordered if it has fewer possible micro-configurations producing the same macro-state. In the case of autocatalytic reactions, the availability of more possible macro-states changes the ratio in favour of the ordered macro-state. Therefore, the nonlinear nature of autocatalytic sets implies an ordered state depending on multiple realizability at the macro level, which might help to reveal the emergence of mechanisms that can tolerate perturbations. A metastable state at the macro level which is not functionally dependent on a certain microstate is a distinctive feature of autocatalytic reactions. In this sense, a multiply realizable cycle of nonlinear reactions can be a step to the evolution of systems in which top-down dynamics are dominant.

Life consists of intertwined chains of production, hierarchical organization, cyclic processes, and mutual dependence characterized by an autocatalytic closure at a global level (Kauffman, 2000). In recent studies, autocatalytic sets have been analysed in current biological systems. It has been found out that *E. coli* can form autocatalytic networks in which up to 1800 reactions are implemented (Sousa, Hordijk, Steel, & Martin, 2015), which is the first empirical affirmation of autocatalytic sets in living systems (Gatti et al. 2017). It is claimed that autocatalytic loops are likely to emerge within the ecosystems as well, due to the symbiotic networks where the participants gain positive selection benefit (Ulanowicz, 1997). Emerging networks of mutual selection would drain resources from other species that are out of the symbiotic network, acting as a self-catalysing loop. The idea of spontaneously appearing autocatalytic sets is no longer just a hypothesis. Still, concerning the origin of life, in the absence of an observation of a chemical system that can exemplify first transitions to living systems, one could object that aforementioned theories are mostly based on models, which remain to be empirically proven.

Studies on autocatalytic sets indicate an interesting potential in terms of developing a unified account of self-organization. The experiments and models suggest that collective autocatalysis as a form of regulative self-organization does not have to be a given from the beginning, but it could emerge due to transitional self-organization. Moreover, as the autocatalytic sets are dependent on establishing reciprocal relations, the emergence of higher organizational levels might be possible in nested structures, which is expressed by the notion of “autocatalytic sets of autocatalytic sets” (Hordijk et al., 2012), This implies that collective production of the system’s parts, which has been defined as a characteristic of regulative self-organization, can also emerge spontaneously. In other words, conglomeration of the cycles of chemical reactions could be transformed into basic forms of biological regulation. Sure enough, this is still far from explaining the self-organization of the modern organism. Yet, autocatalytic sets are essential in terms of showing the connection between spontaneous dynamics of order and biological regulation. In higher forms such as multicellularity, it is not possible to prove this connection directly, as in that case spontaneous organization cannot lead to biological regulation by itself.

Conclusion

In this chapter, I gave a historical outline of the studies on self-organization which was necessary to introduce the diversity of approaches to the account. I distinguished emergent dynamics of order from the regulative self-organization that is central to biological autonomy. I have identified two different contexts in which emergent dynamics of order are involved. One of them is a type of transitional self-organization, which involves the emergence of patterns, and the other one concerns the role of self-organization in the functional integrity of an organism. I also argued that these two dynamics are intertwined in real systems, and briefly discussed the role of self-organization in evolution.

The distinction that I suggested between transitional and regulative types will be a conceptual basis for developing an integrative approach concerning biological organization in the following chapters. As the main problem of this thesis, I focus on the self-organization of the organism. In this regard, acknowledging the physical basis of life’s organization is essential, which is why it was necessary to review theories such as thermodynamics. As will be discussed in the next chapter, there are different approaches to the organism’s autonomy, in which the role of either self-organization or equivalent concepts is widely discussed. Some contemporary accounts dealing with biological organization struggle to identify peculiarities of life within a general understanding of emergent order. This is why the dynamics of order in non-living and living systems must be addressed to make it possible to both bridge and distinguish these dynamics.

Chapter Two

Life As Organization

Introduction

In the first chapter, I made a distinction between regulatory self-organization of the organism and transitional self-organization that brings unprecedented changes in the systemic whole. I also emphasized that life's organization is inclusive of, yet beyond the spontaneous dynamics of order. Now, I will focus on life's organization with an aim to clarify the ways in which specific regulatory structures are dependent on matter's potential for organization. Life's organization is multifaceted; hence it is beyond the remit of this thesis to offer an exhaustive account of the topic. In this regard, only certain problems will be covered in so far as they contribute to the explanation of the organism's individuation dynamics. More specifically, in this chapter, I will discuss the issues within the organizational approach, which develops an anti-reductionist view towards life. This is a continuation of the historical review that I started in the first chapter, as I consider accounts that critically examine the notion of self-organization. With this discussion, I intend to show why self-organization is preferable to alternative approaches. Within the organizational approach, only some of the theoretical lines are open to the notion of self-organization.[26] Two philosophical approaches that I will address are autopoiesis and the autonomous perspective, which are the theories that have been developed to explain biological autonomy. Self-organization also promotes the idea of biological autonomy. However, the perspective of self-organization that I adopt in this chapter has other implications beyond biological autonomy. Autopoiesis and the autonomous perspective, either openly or implicitly, take a critical attitude towards self-organization. Although some

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[26] This is a controversial issue that depends on how self-organization is defined. Thus, as I will mention some cases in this chapter, different scholars sharing the same perspective sometimes have different opinions on self-organization.

proponents of these approaches are not critical towards using the concept of self-organization, and even consider the relevant ideas as a theory of self-organization (Zelený, 1977; Weber & Varela, 2002), I insist on the inconsistency between self-organization and its alternatives. This is because, contrary to the attitude of these theories that subsume self-organized processes under their title concerning living organization, I argue that self-organization represents a universal tendency according to which characteristics of living organization are contextualized in a broader context. The availability of certain types of patterns such as causal loops (see Section 2.2) for building complex organizational structures underlies this universal aspect. By elaborating this point, I aim to give a further account concerning why I claimed in favour of a systematic approach towards self-organization in the first chapter. I will also discuss how this universal aspect is associated with life's organization. Self-organization is not to be considered as a law of nature, since it is a phenomenon of historicity and evolution. Instead, it is related to the self-maintaining nature of certain causal forms such as circular causality.

I start reviewing the ideas on self-organization from the early attempts in philosophy, as I trace back the roots of organizational approach (Section 1.1). The modern discussion began with John Locke and Immanuel Kant, and from a contemporary perspective, organisms are considered Kantian wholes, as they are both the means and the ends of themselves (Kauffman, 2014).[27] Then, I discuss autopoiesis and the autonomous perspective, which were put forward within the organizational approach (Sections 1.2 and 1.3). In particular, I address controversial issues as to the role of self-organization that I summarized in my main argument above.

After reviewing relevant theories, I try to show why a general theory of self-organization is to be preferred to the alternative approaches. First, I clarify the essential points of my understanding of self-organization: Although there is a universal basis, self-organization points to a historical tendency rather than a law-

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[27] As mentioned in the first chapter, Kauffman (2014) expanded this notion to his account of autocatalytic sets.

like explanation of the world (Section 2.1). This is crucially important for my specific focus on the ontogeny of the organism in the following chapters. Second, I examine the relation between circular causality and self-organization (Section 2.2). The circular form of the regulative organization in organisms has the ability to regenerate itself against perturbations, which makes organisms more robust in comparison with non-living causal cycles.

1. Quest For the Organism

Below, I explain how the contemporary ideas concerning the organism have been shaped since the Enlightenment, and how a general philosophical attitude, which is sometimes referred to as the organizational approach (Moreno & Mossio, 2015), has developed. Self-organization, the autonomous perspective, and autopoiesis are different perspectives within the organizational approach, whose common themes are relational ontology (see Chapter 4), biological autonomy (self-maintaining form of the organism), and circular causality (see Section 2.2). In theoretical biology, these themes have been investigated in the research tradition of relational biology, which goes back to Nicolas Rashevsky, Robert Rosen, and Howard Pattee. As I discuss below, especially the autonomous perspective is influenced by the main claims of relational biology, whereas autopoiesis promotes relational ontology on a rather interdisciplinary ground.

1.1 Early attempts in philosophy

This section examines the historical background in which ideas related to self-organization of the organism have been shaped. In *Critique of Judgement* (1790/2008), Kant defined the concept of self-organization for the first time, which was often found quite convenient for the modern context (Kauffman, 1970; Weber & Varela, 2002), and which has been revived in the recent discussions of philosophy of biology. Many of these late interpreters have focused on the reflections of a controversy between mechanistic worldview and biological organization. Below, I consider the historical roots of this controversy as well as other philosophical problems of life’s organization that persisted.

I have mentioned in the first chapter that regulative self-organization concerns the dynamics of individuation within the organism. Historically, this way of understanding can be traced back to the first ideas on the material basis of the organism's identity. Realizing that what makes the organism different from non-living material is nothing but its organization enabled a naturalistic account of these individuation dynamics. As a dualist interpretation, René Descartes' mechanistic explanation considered organic matter as internally inert, in contradistinction to the soul's activity that is non-material. McLaughlin (2001) points out that this conception has started to change in modern science, which abandoned the idea of the soul and considered organism "as a system that remains identical to itself by renewing its parts and assimilating anorganic matter to its organic structure" (p. 173). For the first time, John Locke remarked on the distinction between the identity of a mass of particles and the identity of the organism. The former consists in the physical identity of the components, as the identity changes when the particles change, whereas the latter does not lose its identity when the components change because there is a constant activity of replacing the parts. The idea that something can be reproduced without being decomposed or losing its identity emerged in the seventeenth century and became widespread in the eighteenth century biology (McLaughlin, 2001). During this period, reproduction did not have today's meaning of producing offspring, but it meant re-making itself. Georges-Louis Leclerc de Buffon, who was a prominent naturalist of the eighteenth century, united the biological activities of generation, nutrition, growth, and propagation under the concept of reproduction, thereby paving the way to an understanding of organisms as self-reproducing systems.

Buffon's views influenced Kant's conceptualization of the organism as a natural end (McLaughlin, 2001). Kant considers the organism as a natural end (or natural purpose) by claiming that it is both the cause and the effect of itself. This is based on the fact that the parts of the organism can be united within a form without an external agent. An organism is an organized natural product "in which every part is reciprocally both end and means" (Kant, 1790/2008, p. 202), since every part of an organism depends on and also serves to the existence of other parts. Kant states that an organism is self-organized in different aspects: first, as to producing offspring, meaning that it reproduces as a species; second, as an individual by transforming external substance into its own components; and third, as to the relations between parts, since the growth and reproduction of each part is necessary for the whole. In an organism, the interdependency between parts is self-organized because parts are not only functionally integrated, but also reciprocally produced by each other. Kant compares organisms to artefacts, which is a comparison that goes back to Aristotle (Zammito, 2006). He emphasizes that we can understand the apparent design of organisms as analogous to the design of artefacts, although organisms don't need an external designer. In an artefact such as a watch, parts exist due to the whole's function, too. However, this does not exhibit self-organization, since the parts are integrated by means of an external designer. Thus, functional interdependency between parts is a common property of artefacts and organisms, whereas only in the latter production of parts is reciprocally implemented (Kant, 1790/2008). The uniqueness of biological interdependency in Kant's thought can be understood through the functioning of organs. For example, functioning of the heart is necessary for the continuity of other organs and the body, and vice versa. But beyond that, the heart is materially produced due to the existence of other parts, as the replacement of muscle cells depends on protein synthesis. In a multicellular organism, cells are regenerated at different rates. For example, in humans, a red blood cell is replaced every 4 months, a liver cell every 6 months to one year, and a fat storage cell every 10 years – whereas a cell of the central nervous system is used for the lifetime.

Due to the interdependency between parts, organisms are referred to as Kantian wholes (Longo, Montévil, & Kauffman, 2012), which can be considered as a theoretical basis of organizational approaches towards life. As will be discussed in more details below, reciprocal reproduction of parts is also basic as a minimal condition of life, which is associated with a protocell that can produce its membrane (Gánti, 2003; Luisi, 2006): A self-producing chemical activity that synthesizes its membrane material can isolate itself from the outer world and thereby stabilize its internal processes, as the membrane can selectively intake the material that is to be used in the self-producing reactions. As a precursor of organizational approach, Kant suggested the reciprocal nature of organization instead of essentialist elements due to explaining the distinguishing aspects of living systems. In this regard, reconciliation of the mechanical forces that were analysed in a Newtonian paradigm and the self-reproducing, purposive characteristics of the organisms appear as an essential problem that Kant discusses.[28] One interpretation of Kant suggests that Kant's account should be understood as attempting to naturalize teleology. Yet, there are controversies on the philosopher's views on this. Zammito (2006) points out that a core problem concerning the organism since Aristotle has been intrinsic purposiveness, and on this issue, Kant's attitude was in favour of mechanistic explanation on a Newtonian basis, ascribing only a descriptive role to biology. In this sense, Kant's explanation differs from Aristotle's emphasis on self-motion because the latter presumes a causal power for animals that is not present in lower forms of being (see Chapter 4 for details). Kant famously claimed that there would never be a Newton of the blade of grass, which is interpreted as a reflection of an epistemological deflation due to Kant's scepticism towards a scientific explanation of life (Zammito, 2006). Internal purposiveness is inconsistent with mechanistic explanation in which there is only place for efficient causes. This dilemma brings us to the problem of teleology, and in particular, the possibility of mechanistic explanations for purposeful activities. Kant thought that teleology is a regulative, but not a constitutive principle, which implies that teleology has a heuristic role in the explanation of the mechanistic causes. On this basis, Kant's strategy was to restrain organism's organization to a notion of design that is in fact originated in our agency, which means that purposiveness is something we ascribe to organisms similar to the function of artefacts. Therefore, Zammito (2006) asserts that "if biology must conceptualize self-organization as actual in the world, Kant's regulative/constitutive distinction is pointless in practice and the (naturalist) philosophy of biology has urgent work to undertake for which Kant turns out not to be very helpful" (p. 766).

How relevant is his definition in terms of the organism's regulatory self-organization, then? Despite the problems that are pointed out by Zammito (2006), I believe that Kant's description based on the reciprocal reproduction of the parts set a ground for recognizing the phenomenon. This early description obviously does

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[28] As will be explained later in this work, self-organization relates to this discussion in terms of the organism's form.

not completely overlap with the non-equilibrium condition of self-organization, as Kant's definition could not foresee the contributions of nonlinear dynamics. Yet, it is a preliminary idea in the sense of considering organism's existence due to its activity. Kant investigated the basis of organization at the level of the organism, which I propose, makes him a foreshadower of the contemporary notion of self-organization at least in this respect. This is supported by the general scientific attitude of his time. Kant was involved in the theoretical discussions concerning development and evolution, and there was an intellectual interaction between his philosophy and the prominent figures of the German biology, Johann Friedrich Blumenbach in particular (Lenoir, 1980). Also, the ideas of Kant on the organism have partially influenced German traditions of romantic natural philosophy and organismic biology (Weber & Varela, 2002). As he was closely following the biological research of his time, his definition of self-organization was probably inspired by the discovery of the regeneration capacity of hydra (Molina, 2010, p. 26).

On the other hand, the inconsistency between internal purposiveness and mechanistic explanation continues to be a conundrum of causation that is still debated in different ways. As is well known, Kant's main philosophical views, which are built upon a convoluted way of thinking concerning our conceptualization of the world and the nature of causation, are highly influenced by Newton. Spontaneous dynamics of pattern formation, which is acknowledged in the contemporary theory, was not acceptable within this worldview, as it would imply a radical diversion from mechanical determinism, even beyond the compromise due to the reconciliation of purposiveness. As a matter of fact, Kant enunciated his thoughts on this by stating that the formation of life's organization cannot be ascribed to the role of chance and spontaneity, which he cites as the claims of Epicurean atomism (Kant, 1790/2008, pp. 219-220). This appears to be a drawback in terms of transitional self-organization, since modern studies show that spontaneous order indeed has a role in life's organization.

A point of similarity between Kant and the contemporary approach to self-organization is that he did not accept preformationism, which considers the development of the organism as an unfolding process that is determined from the beginning. As an alternative to preformationism, Kant supported Blumenbach's theory of epigenesis that favours the sequence of developmental steps. Metaphysical reflection of this theory is the assertion on nature's formative force against the idea that everything is determined from the first moment of creation. In biology, this notion of epigenesis is termed as *formative drive (Bildungstrieb).* Kant (1790/2008) remarked that in this principle, organization of nature emerges as a formative impulse beyond a simple mechanical force (p. 253). A main issue of biology in Kant's era was how the forces of life enable – at least seemingly – purposeful development of living things. Even though this Kantian research project has almost ended in the nineteenth century, Moreno and Mossio (2015) suggest that a similar attitude has re-emerged in the early twentieth century. They claim that there is a parallelism between the Kantian definition of the organism as a "natural purpose" and the organicist approach of a group of biologists that formed "Theoretical Biology Club", which was represented by Joseph Henry Woodger, Joseph Needham, Conrad Hal Waddington, and Dorothy Maud Wrinch (Moreno & Mossio, 2015, p. xxv). As a response to growing tendency of reductionism based on molecular biology, these biologists emphasized the implications of the holistic nature of the organization of the living systems.

What was the dynamics that drove biology away from the organicist approach in the first place? Webster and Goodwin (1982) draw attention to a transition towards a primarily history-based approach towards science in the nineteenth century. Not only Kant, but also rational morphologists such as Georges Cuvier and Étienne Geoffroy Saint-Hilaire were attached to the ideals of Enlightenment to establish a mathematically based natural science inspired by Newtonian mechanics. A general belief of this time was that universal and ahistorical necessities of "being" underlie the diversity and temporality in the appearance of things. Therefore, the main approach of rational morphologists was based on explaining biological diversity in terms of "the laws of form" that point to the internal constraints, either as a reflection of functional harmony or structural conformity. In the nineteenth century, the centre of the natural science has shifted from "being" to "becoming" (Webster & Goodwin, 1982, p. 19), as a consequence of which historical development of the form has become the main question concerning the organism. The philosophical roots of this shift were both in German Romanticism, which produced August Weismann's preformationism, and in Natural Theology, which Webster and Goodwin (1982) claimed to have influenced Darwinism. In German Romanticism, the understanding of the organism as a self-organized totality has been replaced by a holism according to which form is determined by a spiritual organizing centre instead of a material reciprocity of the parts. On the other hand, the influence of Natural Theology is claimed on the basis that Darwinian tradition has replaced the intervention of a divine creator with that of natural selection. In that regard, albeit Darwinism did not directly contradict the structuralist conception of form, it ignored this aspect of research, as the dynamics of form is reduced to a functional explanation of traits that are externally determined due to natural selection (Webster & Goodwin, 1982, p. 23).

Some of the concepts that I discussed here, mechanistic explanation, form, and structuralism, should be paid a special attention due to their role in the ensuing controversies over self-organization. I will go back to these problems in more detail in the last chapter. The essential claim of mechanistic explanation that is in question here is the consideration of matter as inert without external causes, which I believe to be reflected in Kant's struggle to reconcile mechanical forces with the intensive purposiveness of the organisms. One could argue that this is an unsolved problem that persists in contemporary philosophy of biology in the attempts to develop concepts to replace or naturalize teleology. In contrast, I propose that self-organization has now paved the way to find a solution that lies in the emergent condition of an endogenous transformation that determines the systemic context of the causal relations (see Sections 2.1 and 2.2).

1.2 Autopoiesis

As I have already discussed briefly in the first chapter, cybernetics established a theoretical basis that shaped the organizational approach. In this approach, it is emphasized that living systems cannot be understood by merely studying the physical properties of the components involved, and instead, specific attention should be directed towards internal relationships of living systems. This relational view contributed to the development of a non-reductionist view concerning life which is also held by autopoiesis. However, as I show below, there is no consensus towards self-organization among the proponents of autopoiesis. In this section, my aim is to point out the distinctive aspects of self-organization and the criticism directed against autopoiesis from the perspective of self-organization. I aim to demonstrate how these criticisms are not merely reflective of a dispute between choices in terminology, but rather expose fundamental problems for the theory of autopoiesis. First, autopoiesis considers contingent factors merely as a negative aspect of organization that should be tolerated. This one-sided approach disregards the role of spontaneous order. Second, autopoiesis proposes an idealist interpretation concerning the operational relationship between the organism and its environment (Swenson, 1992). This is based on an emphasis that external stimuli mechanistically determine the action of the organism. However, this kind of deterministic relation between the perception and action denotes only a basic mechanism of cognition, which is inconclusive as to building the identity of the organism. The final concern is that autopoiesis is focused on the closure of the organism in an over-simplistic way, which leads the theory to overlook the existence of multiple levels of organization. Whilst it is true that autopoiesis does not necessarily exclude the possibility of multiple levels of organization, the theory denies that organization is primarily a matter of ecological emergence.[29] Therefore, contrary to the main assertion of autopoiesis, it is not possible to define the minimum condition of life by merely focusing on the properties of the organism, or the proto-organism.

Autopoiesis, which was originated from the Chilean biologists Humberto Maturana and Francisco Varela, refers to the self-producing character of living systems. The concept was originally put forward in biology, but then applied to cognitive science, sociology, and systems theory (Mingers, 2002). The application of this concept to these areas is known under the title of second order cybernetics, which presupposes that, in distinction to the first generation of cybernetics, the observation of systems is made not from the outside, but from within the system

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[29] As mentioned in the first chapter, ecological emergence is associated with the transitional dynamics of self-organization because increasing complexity on Earth can be considered as a transition to a correlated state.

(Van de Vijver, 2013). As I discuss below, this kind of shift brings other philosophical problems concerning objective criteria for identifying organization. Moreover, the relation between autopoiesis and self-organization is a controversial issue, since there are different interpretations concerning the relationship between these two theories. For example, Maturana believes that self-organization is not an applicable term in terms of their theory of autopoiesis (Maturana, 1987; Collier, 2004), whereas Jantsch (1980), Zelený (1985), and many others consider that autopoietic systems are self-organized.

Let us first look at the definition of the autopoietic system before discussing the main issues with this approach:

> An autopoietic system is defined as a network of processes of production (synthesis and destruction) of components such that these components: (i) continuously regenerate and realize the network that produces them, and (ii) constitute the system as a distinguishable unit in the domain in which they exist. (Varela, 1994, p. 26)

Autopoiesis is a minimum condition of life that involves a repetitive process of self-production. The autopoietic system is an intradependent structure that is characterized by organizational closure. Closure refers to the internal operation of the system working as a network of feedback loops that maintain its structure against a certain degree of external perturbations. This is possible due to the creation of boundaries that isolate the system from its environment. Thus, an autopoietic system is operationally closed, relational, functionally invariant, and distinguished from its environment by its boundary.

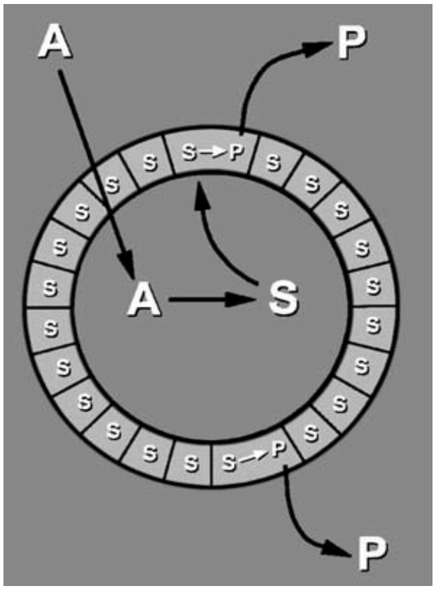

Figure 2.1 Self-production of the cellular boundary. External material is synthesized by the autopoietic system to produce the membrane as boundary (from Luisi, 2006, p. 172).

In contradistinction with allopoietic systems, “determined by processes which do not enter in their organization” (Varela et al., 1974, p. 189), an autopoietic system is autonomous, meaning that it is the product of its own operations. A basic autopoietic system is the cell as a unicellular organism, which functions as a metabolic cycle producing its own membrane that constitutes its boundary (see *Figure 2.1*). Weber and Varela (2002) state that a multicellular organism is not an autopoietic system in itself, although it "inherits its autonomous nature and sense-making qualities through the configuration of its neural identity" (p. 115). The idea of the closure as a minimal condition of life is utilized in compartmentalization theory concerning the origin of life, which asserts that a protocell condition that isolates internal chemical activities from the environment is necessary for life to begin (Luisi, 2006; see Chapter 3).

The theory of autopoiesis considers the living system as a type of machine that is able to produce itself. In this sense, it deals with the abstract relational properties of this machine that are independent of the properties of its real components (Maturana & Varela, 1980, p. 77). Maturana and Varela (1980) state that their theory is a continuation of the cybernetic conceptualization of the homeostatic machine. However, cybernetic machines operate on external parameters, whereas autopoietic machines are self-referential. Here, self-referentiality implies cognitive operations that are not based on representation, but on the action of the organism. According to this approach, life depends on processual invariance due to the coupling between the organism and its environment (Maturana & Varela, 1992). Chemotactic movement of the bacteria cell is given as an example of this action-based cognition. This movement depends on a certain set of rules, according to which the bacterium moves towards the sugar ingredient, avoids the obstacle in the environment, tumbles about, etc. This is due to the sensorimotor correlation in which environmental stimuli are coupled with the motor activities in the internal structure such as a change in the direction of flagella beating (Maturana & Varela, 1992, pp. 148-149). The authors give this example to prove that behavioural changes that serve the internal invariance are the point of interaction between a living system and its environment, which is called operational closure.

Autopoiesis suggests analysing life's organization from the viewpoint of a relational and processual ontology, which can be considered as a development of ideas that can be traced back to Kant and cybernetics. Autopoietic organization is defined as a unity of a complex system by a network of productions (Varela et al., 1974, p. 188). This emphasizes the overwhelming regulatory capacity of relations over the components of a system. Since this notion is also basic to the organism's self-organization, it seems, prima facie, plausible that autopoiesis and self-organization have a common basis. Indeed, there are certain common themes such as the role of metabolism in the steady flow of materials through the organism and interconnectivity among the components. Moreover, theories of self-organization and autopoiesis both emphasize that processual organization is an alternative to gene-centric explanations (Luisi, 2006, pp. 156-157). On the basis of these common themes, it has been claimed that autopoiesis, self-organization, and systems research are united in so far as they propose that an autonomous agency is essential to living processes (Weber & Varela, 2002, p. 115).

However, upon closer inspection, it becomes evident that the interpretation of life's organization proposed by autopoiesis is not utterly consistent with the main claims of self-organization that I discussed in the first chapter. The importance of transitional dynamics of self-organization is disregarded in autopoiesis, since the organization of the self is regarded as a given (Maturana & Varela, 1992). According to Maturana, as the self does not exist from the onset of interactions, "self-organization appears to require a sort of lifting oneself by the bootstraps without having even boots at the beginning" and therefore, self-organization "appears to be an oxymoron, or at least a misnomer" (as cited in Collier, 2004, p. 151). In this regard, Maturana's approach overlooks the role of self-organization in producing individuation as a system's inherent capacity (Collier, 2004, p. 169). In far-from-equilibrium conditions, order emerges through fluctuations due to the randomness inherent within the system. As I emphasized in the first chapter, this dynamic is incorporated in the regulative system of the organism by recognizing the underlying contingency of the biological organization (see Chapter 4). However, autopoiesis describes biological organization as something that is in conflict with contingency. Reducing life's functionality to the elimination of contingent factors presupposes that stochastic elements are necessarily negative, whereas this is not the case for actual biological processes. Stochasticity might be a positive element in life's organization, e.g. stochastic elements in the expression of genotypes lead to the phenotypic diversity of populations, which might contribute to the creation of novel adaptive solutions (Kærn, Elston, Blake, & Collins, 2005). In a single organism as well, noise-induced processes contribute to morphogenetic patterns. Besides, in several regulatory tasks such as the functioning of the immune system, contingency has a positive role in the exploration of new organizational possibilities (see Chapter 3). As I will explain in the following chapters, models of self-organization successfully recognize this contingent basis instead of the misleading presumption of precise mechanistic control by autopoiesis.

To save autopoiesis from the abovementioned criticism, one could argue that predominant factors underlying the autonomy of an organism are regulative, and thus autopoiesis is consistent with regulative self-organization. However, this kind of reconciliation would not resolve the problem due to negative consideration of contingency in autopoiesis. As explained in the first chapter, individuation dynamics appear due to the nonlinearity of systems, and organisms are not exempt from spontaneous emergence of order, which involves the positive role of contingency.[30] Moreover, the account of life's organization proposed by autopoiesis is based on functional invariance, since the nature of relationality does not change through its adaptation to external conditions. This is a one-sided presumption that only considers the static aspect of organization by ignoring the generative processes within the organism (DiFrisco, 2014, pp. 509-510). The notion that internal relationships remain invariant would lead to disregarding the changes through the lifespan of the organism. As pointed out in a critical comment by Swenson (1992), from the viewpoint of organizational invariance, "the organization during the growth of an acorn into a full-size oak tree remains the same" (p. 209).

The abovementioned problem is related to the abstract nature of autopoiesis. Autopoiesis presupposes the existence of abstract relational properties of the system prior to any knowledge of specific components that are assembled to form specific systems. This presupposition is supported by the further distinction

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[30] In the following chapter, I will clarify this issue further by addressing how spontaneous order becomes efficient at different levels of organization, thereby contributing to a hierarchy of organization.

between the organization of a system from its structure. According to this distinction, organization refers to the relations that make a system a member of a certain class, whereas structure refers to particular components in unity, which realizes the organization (Maturana & Varela, 1992, p. 47). Autopoiesis is not primarily concerned with the structure of life, but it is concerned with the organization of life. The organization is relational and abstract, and it can become concrete in various structures. Fleischaker (1988) objects this claim by pointing out that "abstract systems cannot be candidates for living systems" (p. 42). Since abstract systems are constructed by humans, they are put forward as generalizable formulas of living systems, and therefore should not be confused with the physical basis of these systems. Maturana and Varela begin with the abstract autopoietic condition as a given, and derive the physical by comparing to the abstract. However, on the contrary, understanding living systems should be based on the observation of the physical (Fleischaker, 1988). In a similar vein, autopoiesis is criticized by the proponents of biological autonomy, which insists on a reconceptualization of closure (Moreno & Mossio, 2015). Autopoiesis emphasizes the minimal organizational logic of life at the expense of disregarding the chemical and physical properties, and in particular, thermodynamic basis of living systems (Ruiz-Mirazo, Peretó, & Moreno, 2004). The autonomy of biological systems depends on both organizational closure and thermodynamic openness of these systems (Moreno & Mossio, 2015, p. 5). Closure is determined by the constraints on the flow of energy through the living system (see next section for details of this approach). Swenson (1992) makes a similar point by stating that creative aspects of organisms and the emergence of order are ignored in autopoiesis.

The main features of the theory of autopoiesis can be understood as developing from Maturana's theory of cognition (DiFrisco, 2014, p. 506). Maturana and Varela (1992) claim that they are trying to find a middle point between representationalism and solipsism (p. 241), whereas Swenson (1992) criticizes autopoiesis for falling into the latter, which he says to be evident in the claim of "what we do not see does not exist" (Maturana & Varela, 1992, p. 242; as cited in Swenson, 1992, p. 209). According to Maturana and Varela (1992), when we think or express what there is in the world, our awareness of the world is limited through the functional coupling between the organism and its environment. Subjectivist idealism resides in the claim of autopoiesis that organisms can invent their rules due to cognitive coupling with their surrounding, for which Swenson (1992) rightly remarks that this makes organisms “the inventor of reality” (p. 209). Although Maturana and Varela (1992) assert that their intention is to avoid representationalism, what they in fact avoid is the possibility of a realist interpretation of the world beyond the limits of our perception, which seems to depend on a conflation of epistemic and ontic bases of knowledge.

The emphasis made by autopoiesis is that functional coupling between the inputs from the environment and the actions that are taken based on these inputs, which is exemplified by the sensorimotor correlation, is fundamental to cognition. I have no objection against this kind of anti-representationalist attitude, and it is not necessarily incompatible with self-organization. On the contrary, similar ideas have been expanded to cognition based on the self-organized constitution of action-perception cycles (Swenson & Turvey, 1991; Juarrero, 2004; Kelso, 2016). However, merging the ontological and empirical bases of knowledge within the operational closure has a more profound implication than merely claiming for the cyclic nature of cognition. The distinction between the object and the subject would be blurred because the perceiver would be defined by the perceived, and vice versa. The subject perceives things and makes decisions based on what is perceived; yet the identity of the subject cannot be reduced to the world perceived by the subject. Beyond a mechanistic coupling with the surrounding conditions, the subject can imagine counterfactual situations, anticipate, or create an identity by reflecting the momentous self-perception through an extension of time.

As Zolo (1990) points out, if the subject’s identification of the object within its observation is considered as impossible, then it also becomes “meaningless to postulate the existence of a ‘logical isomorphism’ between the substratum of the observation and the language of description” (p. 69). The body is functionally coupled with the world, but cognitive abilities also enable the organism to perceive its self as opposed to environment. So, contrary to the main claim of autopoiesis, cognition – maybe not in the form of sensorimotor skills, but as the abilities of self-awareness, planned behaviour, and abstraction – contributes to the decoupling of the self, while other ways of interactions such as metabolic activities couples the organism and its environment. Maturana and Varela ignore the fact that the abstraction that is necessary to make statements concerning life requires the organism to possess the cognitive capacity to detach itself from the vicious cycle between the perceiver and the perceived. This aspect of cognitive decoupling from the world, which is manifest in animals with a self-awareness capacity, also includes an array of cognitive abilities that are well beyond the sensorimotor coupling of simpler organisms such as bacteria. On the other hand, even if a basic input-output model of action-perception cycles could be considered as a basis of cognition, this would not be sufficient to reduce self-maintaining systems to cognitive functions. Other examples aside, the existence of non-living forms of self-organization, which are obviously not cognitive, proves that systems might gain the capability to tolerate perturbations in various ways.

Last but not least, autopoiesis understates the importance of ecological dimension for life. By reducing life's minimal condition to the causal closure of the organism, it ignores that the organism's organization is dependent on an environmental network at the most fundamental level. As pointed out by Meincke (2018), there is a one-sided consideration of the environment in autopoiesis which focuses solely on the negative aspect of perturbations (p. 4). In fact, autopoiesis does not take environmental aspect into consideration beyond an extension of the organism. Some aspects of autopoiesis are in line with a general account of self-organization. For instance, self-maintaining cycles undertake the constant inflow of energy, and other cyclic processes such as the circadian cycle enable organisms to adapt their environment. Nevertheless, life is primarily an ecological organization because metabolism is a chemical process that requires available conditions that sustain its dynamism. Therefore, the organism's self-maintenance would be impossible without an ecological cycle through which energy sources are replenished, which is why the minimal conditions of life that are identified by autopoiesis are not fulfilled at the level of organism, but at the level of ecological cycles.

The requirement of the ecological dimension for understanding the organism becomes apparent from the thermodynamic conception of the emergence of life, which is mostly ignored by autopoiesis. Considering the underlying non-equilibrium condition that requires a constant energy flow, availability of energy is crucial for organisms. If it were not for ecological basis of disequilibrium, organisms would not have access to this flow of energy. Furthermore, the main elements of living systems – hydrogen, oxygen, and carbon – are limited on Earth, and an ecological circulation of these elements is necessary for the organisms to readily have access to them. The necessity of these fundamental conditions is emphasized in research on the life's origin, which deals with the minimal condition of life from historical perspective. According to this approach to minimal condition of life, since the sustainability of the interactions between the organism and its surrounding is essential, the fluctuations of the organism's life cycle should be synchronised with the fluctuations in the ecological conditions, e.g. there should be a cycle between reducing and reduced elements for the sustainability of life's chemical interactions (de Duve, 1995). For example, life on Earth depends on the autotrophic life form, whose energy intake is due to the attraction of electrons by using solar energy. As is known, photosynthesis turns solar energy into chemical energy; hence it can be used by other species as well. For the ecological continuity of photosynthesis, oxygen and carbon cycles are crucial. In today's ecosystems, oxygen is the final electron acceptor for aerobic organisms and therefore it must be available in nature for these organisms to survive. Concerning the early conditions of Earth in which life has emerged, it has been hypothesised that a primitive ecological cycle could have existed between sulphur and iron, in which iron was the reducing element (de Duve, 1995). As is seen in this example, circulation of elements and energy can be addressed as a relational property that applies in different actual conditions, which is in a way parallel to the distinction between structure and organization that was made by autopoiesis. Yet, in this context it is a relational property due to ecological dimension which is above the level of the organism.

The availability of ecological cycles is an implicit background presupposition for any conception of the minimal condition of life at the organism level. The latter would not be possible in the absence of the former. Hence, since Alexander

Oparin, the question of life has been addressed as a transformation of biosphere that enabled the emergence of complex life cycles. In fact, it is stated that the theoretical gap concerning the ecological condition was noticed by the pioneers of autopoiesis, as Varela himself had an attempt to reformulate the organization in conjunction with the ecological niche (see: Varela & Goguen, 1978), but it seems that the revision of the theory in this respect was never completed (Andrew, 1979).

There is no abstract formulation of the organism, and therefore no type of autonomous unit including the one that is suggested in the autopoietic account can be supported without acknowledging ecological context. In contrast with the idea that a theory can describe the minimal condition of life by merely focusing on the organism, levels of organization from biochemical activities to ecosystems are crucial. Life on Earth is a history-dependent process, and any attempt to formulate abstract principles, including the efforts to develop artificial life forms, are derived from the observation of actual life forms, since any consideration of the minimal condition of life is determined within the context of the biosphere. Autopoiesis defines the organization specific to living systems in terms of abstract principles that ignore both the physical dynamics of life and historical background that enabled the minimal condition of life. As I discussed in the first chapter, chemical basis of life is a question that requires dealing with the transitional dynamics of self-organization. In this sense, autopoiesis is neither within the scope of, nor an alternative to the ideas of self-organization.

1.3 The theory of biological autonomy

In this section, I address the theory of biological autonomy, which is also called *the autonomous perspective*, pioneered by Alvaro Moreno and Matteo Mossio mostly within the scope of the research tradition of organizational approach that includes, cybernetics, autopoiesis, Howard Pattee’s views on closure, and Stuart Kauffman’s notion of work-constraint cycles (Moreno & Mossio, 2015, pp. 1-11). My specific questions are how the autonomous perspective explains the organism’s individuality, at which points it is critical or supportive of the principles of self-organization, and how it can contribute to broader concerns raised by this thesis such as the processual nature of organisms. The autonomous perspective deals with the underlying dynamics of the organism's individuality in the face of constant energy flow, contingency, and dissipation. In other words, it questions how the organism maintains its organizational stability despite being a dissipative system. This approach is partially based on the revision of the notion of closure, which was first put forward in autopoiesis (Varela, 1979). As the reader will recall, autopoiesis is criticized from the perspective of organizational account for not considering the thermodynamic basis of life (Ruiz-Mirazo et al., 2004).[31] The revision of organizational approach by the autonomous perspective involves the claim that the organism's organization is determined by the closure of constraints acting on the energy flow, thereby outbalancing the increase of disorder. Despite this positive contribution, I argue that the autonomous perspective is inadequate for acknowledging the principles that are put forward in the theory of self-organization. In particular, there is a lack of emphasis on emergent order in the former account due to its consideration that self-organization is restricted to non-living phenomena.

The notion of constraint and its application to living systems and evolution must first be explained as these principles underpin the autonomous perspective. Moreno and Mossio (2015) are influenced by Pattee's views on this issue. They state that they have an intellectual debt to Pattee, in particular to his understanding of the notions of constraint and closure (Moreno & Mossio, 2015, pp. 24, 134). In physics, the constraint denotes any property of the environment of a system which reduces the degrees of freedom; generally expressed as an equation that formulates the relation between different variables. Here, the environmental properties refer to the geometrical conditions in the surroundings, e.g. an inclined plane acts as a constraint on the movement of an object that slides onto it. As highlighted by Pattee (2012), although the notion is applied to the physical basis of life, the implications for the origins of life and evolution is more complicated than the textbook definition of the constraint. First, constraints are different from a law of nature, since "a natural law is inexorable and incorporeal, whereas a constraint can be accidental or arbitrary and must have some distinct physical embodiment in the

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[31] Moreno and Mossio (2015) state that another source that influenced their theory is Kauffman's work cycle in which exergonic and endergonic reactions are coupled in order to harness the release of energy as heat (see Chapter 1).

form of a structure” (Pattee, 2012, p. 82). Second, a physicist’s conception of constraints is always associated with a hierarchy of levels, since constraints apply to a collection of particles (Pattee, 2012, p. 98). Based on this, Pattee (2012) points out that “a dynamical collection is described as a constraint when there exist equations or rules in a simpler form that direct or control the motions of selected particles” (p. 99), which brings certain implications as applied to living systems (see below). Thirdly, quite similar to Kauffman (2000), Pattee thinks of constraint as a way of questioning the nature of causation and the epistemological basis of understanding causation. As remarked by Schrödinger on the question of life, two different theoretical approaches to causality involves the deterministic description of the microscopic events and the statistical description of the macroscopic events (Pattee, 2012, p. 201). Self-organization due to far-from-equilibrium conditions involves the idea that chance events at the micro level are amplified at the macro level, and stabilized within a new form of organization. Pattee points out that even though Prigogine’s theory on dissipative systems introduces history to the physical basis of organization, in this theory, “the selection of alternative modes is left to chance” (Pattee, 2012, p. 202). When it comes to biological organization, he thinks that neither deterministic description of micro-scale events depending on initial conditions, nor statistical physics can be explanatory. Different from the physical dynamics of self-organization that are based on statistical laws and chance events, self-organization of the living systems is based on symbolic information. According to Pattee, a symbol is “something that stands for something else by reason of a relation, but it is implicit in this concept that the relationship of symbol to referent is somewhat exceptional” (Pattee, 2012, p. 205).

Pattee (2012) claims that symbolic information is the underlying factor of the organism’s organization through genetic regulation and enzymatic activities. Contrary to dissipative systems, there is a selective control of the rate of matter and energy flow within the living systems, which is exerted through the instructions of the symbols. For example, protein synthesis is implemented in this way by controlling the rates of genetic expression and enzymatic activities (Pattee, 2012, p. 206). Physical dynamics of organisms are harnessed by their evolutionary history, which is realized by the closure that determines the organization of living systems. Closure corresponds to the emergence of functionality through the levels of organization:

> Hierarchical control arise from a degree of internal constraint that forces the elements into a collective, simplified behavior that is independent of selected details of the dynamical behavior of its elements. It is the combination of the independence of the constraints on the microscopic dynamics along with the simplification of the collective dynamics which creates what we recognize as integrated behavior or function. (Pattee, 2012, pp. 101-102)

Pattee's (2012) account of closure in the face of non-living self-organization can be interpreted as follows. In far-from-equilibrium systems such as Bénard cells, appearance of correlated relations out of the random movement of molecules creates certain patterns. These patterns produce macro-scale structures belonging to certain kinds, despite the uniqueness of each individual process. In organisms, a similar process across the levels of organization occurs. Yet, contrary to dissipative systems, what characterizes the organism as a specific type of organization is not a direct amplification of certain micro-scale events that are associated with chance, but the regulatory cohesion in which symbols – as amino acid sequences, signalling mechanisms, intercellular interactions, etc. – enable the continuity of form against perturbations by using internal information systems. Pattee (2012) claims that constraints similar to those introduced by artificial devices of measurement are the basis of biological organization from enzymatic activities to natural selection (p. 207).[32]

The distinction between matter and symbol is a core element in Pattee's approach. Although all symbols have material embodiment, symbols cannot be reduced to law-based descriptions of matter, as they are the products of natural selection. Symbols are used by organisms to increase control and survival abilities

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[32] In the context of a broader criticism also calling into question the deterministic worldview, Pattee (2012) discusses the role of measurement and the relevance of initial conditions in a Laplacean way of thinking. He is critical toward the deterministic view based on initial conditions. In particular, he questions the relevance of the complementary models of chance and determinism. The factors that are associated with either chance or determinism are built on non-observable constructs, and a non-observable construct "depends on the observables chosen for the model" (Pattee, 2012, p. 255). Both chance and deterministic factors are necessary as complementary models of a binary way of thinking, even though these are formally incompatible (Pattee, 2012, p. 265). In the fourth chapter, I will go back to this problem in relation with relational ontology.

in a specific environment (Pattee, 2012, p. 214). Any measuring activity depends on reducing the material degrees of freedom of a system to a few semantic references. This is equivalent to the essential role of symbolic information in constraining and controlling living systems. In a measuring activity such as the one that is performed in physics, the symbol-matter distinction is quite clear, yet this is not the case with organisms. Pattee (2012) states that an external analysis of symbolic information and internal utilization of symbols are different. From an external viewpoint, to understand the function of symbols, we need to fully investigate the complexity of mechanisms involved; not only the symbolic role of a gene sequence in the coding of a protein, but also the very material process of protein folding. The computation of the whole complex mechanism across the hierarchy of organization is necessary. However, for the folding to occur within the cell, all that is required is the reading of the base sequence. Thus, within the interlevel causation in which the process occurs, the practical role of symbols is the simplification that enables the required function: “As in the case of measurement, in order to have any useful function, genes must be able to symbolize something without symbolizing everything” (Pattee, 2012, p. 215).

Of course, Pattee’s (2012) theoretical approach to constraints, symbols, and measurement is a detailed one that cannot be fully explained by my short summary above. I have provided an outline of his ideas to clarify how it influenced the autonomous perspective. Before continuing this analysis of the autonomous perspective in relation to self-organization, I will first expose a drawback in the account by Moreno and Mossio (2015). Pattee’s critique exposes problems concerning symbols, deterministic modelling based on initial conditions, and measurement. Pattee’s views – as well as Robert Rosen’s (see Chapter 4) – are developed to address the issues concerning not only biology, but also more general problems within philosophy of science. As I discuss below, in Moreno and Mossio’s (2015) account, there is a notable absence of a debate concerning these epistemological issues, particularly measurement and symbols, even though they adopt other parts of Pattee’s theory that are derived from a questioning on this general basis, e.g. boundary conditions, closure, constraint, etc. Sure enough, it should be admitted that acknowledging all aspects of theoretical questioning is not necessary for developing from Pattee's account. At the very least, it follows that the notion of constraint in Moreno and Mossio's account is descriptive, since the authors move away from some of Pattee's epistemological concerns without offering an alternative. Ignoring these core problems might be one of the underlying reasons of the attitude that is adopted by the autonomous perspective towards the notion of self-organization. As discussed below, Moreno and Mossio (2015) distance themselves from biological self-organization, and consider the phenomenon as limited to non-living area. In this sense, their attitude is deviated from Pattee's view that a theory of biological self-organization requires functionally relating spontaneous generation of order and information-dependent systems, which are considered as two different classes of self-organizing systems (Pattee, 2012, p. 197).

According to the autonomous perspective, a constraint is referred to as an entity that limits other processes without being unaffected by them (Moreno & Mossio, 2015, p. 11). Hence, stabilities within the organism are determined relatively through processes at different paces, e.g. an enzyme catalyses chemical reactions, while it remains relatively unchanged through these reactions (pp. 11-15). The organism's organization is described as a network of constraining processes, as "the organization of the constraints can be said to achieve self-determination as self-constraint, since the conditions of existence of the constitutive constraints are, because of closure, mutually determined within the organization itself" (Moreno & Mossio, 2015, p. 5).

In this context, the autonomous perspective points out that the flow of energy within the living system is restricted in a way toward maintaining its form. Moreno and Mossio (2015) associates the notion of constraint with the role of timescales in the creation of organizational hierarchy,[33] which provides insights for understanding the organism's organization appealing to certain theoretical issues mentioned above. According to this view, the constraint, as an entity, has a static nature in the face of dynamic processes. Moreno and Mossio emphasize that the

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[33] The role of timescales in the constitution of levels of organization is not a new theme. For a review on timescale hierarchies, see DiFrisco (2017b).

organism's autonomy involves additional conditions in comparison with the spontaneous dynamics of self-organization, which is a point that is made by other people addressing the issue (Simondon, 1992; Ulanowicz, 1997; Pattee 2012). Since the underlying problem is explaining the relation between biological autonomy and spontaneous self-organization, I shall further elaborate thoughts of Moreno and Mossio (2015) on this issue. A prominent idea in this context relates to the organism's closure in contradistinction with self-organized systems such as Bénard cells that occur in physics and chemistry (Moreno & Mossio, 2015, p. 16). They contrast non-living self-organization and closure in the following way:

> This makes a clear-cut categorical distinction between minimal self-organisation and biological closure: while in the first case a single constraint is able to determine itself, in the second case self-determination can only be collective, i.e. by contributing to the maintenance of one or several other constraints, each constraint contributes indirectly to its own maintenance, because of mutual dependence. (Moreno & Mossio, 2015, p. 17)

In this account, non-living self-organization is considered a lower type of self-determination, whereas closure is ascribed to a "qualitative change from minimal (self-organisation) to collective (closure) self-determination [that] goes hand in hand ... with a quantitative increase of the underlying complexity" (Moreno & Mossio, 2015, p. 18). Other features that distinguish closure in living systems include: the takeover of boundary conditions (as the physical boundary of an organism is demarcated by a membrane), the coupling of the endergonic and exergonic reactions, the ability to store energy, and a potential for increasing complexity – which refers to the evolvability of organisms.

As mentioned in the distinction in the first chapter between regulative and transitional dynamics of self-organization, the existence of the differences pointed out by Moreno and Mossio (2015) is undeniable, and point to a distinct aspect of life that requires a different type of explanation. The kind of complexity that appears in autonomous organisms is only possible due to evolution, as we would not expect the emergence of self-maintaining cells directly out of a solution containing the basic elements of life. Thus, concerning the distinction between non-living self-organization and biological autonomy, I agree that biologically autonomous systems require a different explaining of their emergence which is characterized with a high capacity of self-maintenance. It goes without saying that we need conceptual distinctions and a different type of analysis for biological autonomy to differentiate the circular causality of living systems (see Section 2.3) from the basic physical dynamics of organization. However, it is also important to recognize that causal cycles are the common basis of organization of both living and non-living systems. What distinguishes organisms is that their complexity grant unprecedented robustness to biological cycles. Spontaneous emergence of order that produces causal cycles is key to understand the relation between living and non-living types of self-organization. Natural selection alone cannot explain all aspects of biological evolution, and therefore the role of spontaneous order is essential (Bonner, 1996; Weber & Depew, 1996). As I explain below, the strong distinction between non-living self-organization and biological autonomy that is offered by the autonomous perspective is an obstacle to acknowledge the common basis of emergent organization.

The emphasis I made concerning the association with general forms of causation requires reconsidering the constraint as an explanatory element of ontogeny. Self-organization is primarily a bottom-up appearance of order that brings transformation of the system in point depending on internally contingent elements. This is the common basis of self-organization that applies to both biological and non-biological processes, which seems to be ignored in the approach of Moreno and Mossio (2015). By denying the common basis of living and non-living self-organization, Moreno and Mossio reject the possibility of a universal principle of bottom-up dynamics. Closure creates a self-driven bedding for energy flow, but this does not mean that once multicellular organization has evolved, autonomy has replaced the bottom-up dynamics by ruling out emergent dynamics of order. On the contrary, dynamics due to the physical properties of matter are reshaped in biological organization by genetic regulation that increases the robustness of biological systems. This also implies that the emergent order is systematically exploited by the organismic organization through the processual dynamics, transitional self-organization is constrained and made a part of the regulative self-organization. Therefore, even though the role of closure is undeniable in self-determination, this does not require giving up the concept of self-organization in biology in any case. As was mentioned earlier, the evolutionary possibility of autonomous systems cannot be sufficiently understood in isolation from transitional self-organization. Autonomous systems are still subject to spontaneous order that occurs at different levels of interactions. As a basic difference, non-living systems rely on an external energy source in a passive way, whereas biologically autonomous individuals are characterised by having the ability to extract their energy in a much more consistent way. A flame is self-organized, but its continuity depends on the system's source of energy, whereas an organism's self-organization allows it to become an active agent of its environment, e.g. the organism can seek new sources of energy.

How should we understand Moreno and Mossio's (2015) emphasis on constraints, then? The answer to this question can be given by considering the examples of constraint described by the authors. For instance, they discuss the role of the membrane in enabling cellular activities and the role of cardiovascular system in the flow of oxygen (Moreno & Mossio, 2015, p. 11). These are the examples that allude to the underlying geometrical nature of constraints, e.g. the membrane is a physical boundary of cellular activities. Formation of constraints depends on relatively unchanging conditions in the face of more rapid processes. This consideration of constraint does not sufficiently explain organizational novelty and emergence due to ontogenetic factors; rather, it reduces the emergence of constraints to an issue of functional explanation, and thus selection. On the other hand, according to an approach of ontogenetic self-organization, the form of the organism is emergent, that is, form is acquired through development and growth. Hence, part-whole relationships should be investigated in this respect. The autonomous perspective does not take this aspect of emergence into account, but only concedes the evolutionary emergence of constraints. It is true that enzymes, cardiovascular systems, and membranes are entities that appear through evolution. Yet, pointing to their role as constraints per se is not sufficient to go beyond the Darwinian approach that explains each trait due to its specific function.

Organisms are self-determining systems, but their appearance as systems of determining themselves is a question of morphogenesis, that is, how the whole, as a dynamic constraint, with several processes of spontaneous ordering dynamics at lower levels of organization, organizes itself. In this sense, the reduction of the degrees of freedom, which is essential for the idea of constraint, not only appears as a static physical condition, but also as a transitional process (e.g. in noise-induced processes). The autonomous perspective points out that constraints are contingent causes in comparison with the laws of physics, as they arise due to the specific conditions of a system (Montévil and Mossio, 2015). However, as it explains constraints only as products of evolution without considering their emergence specifically in the context of ontogenetic self-organization, the ontogenetic emergence of biological constraints from, and continual dependence on, transitional self-organization is disguised. The notion of closure, which refers to the mutual dependence of stabilization factors, points only to aspects of physical boundary and relative stability of processes as the underlying factors of the organism's individuality. On the other hand, spontaneous dynamics of order is fundamental to life's order, which is why a comparison between self-organization and "closure" should take into account that the former is in fact included in the latter. As will be clarified in the following chapter, processual basis of constraints involves not only dynamics of self-assembly that appears with the release of free energy, such as the self-assembly of a phospholipid bilayer, but also a type of "order for free" phenomenon that is hidden in the self-organizing tendency of kinetics. Thermodynamic flow is already sealed by the spontaneous dynamics of order across the lower levels of organization even without the types of constraints that Moreno and Mossio emphasize. This lower-level spontaneous source of order is crucial because if the role of physical factors is not acknowledged, then we could be led to the misconception that biological regulation is simply a matter of mechanistic micro-control and precise structuring. Although the autonomous perspective does not explicitly advocate this mechanistic conception, their account does not resolve the explanatory gap when mechanistic explanation is ruled out, which makes it difficult to differentiate their approach from the machine conception of autopoiesis.

In the previous section, I criticized autopoiesis for ignoring the importance of ecological dimension, and beyond that, for developing its main ideas on the basis of an abstract scheme derived from a self-sustaining cell. The autonomous perspective makes significant advances compared to autopoiesis because it recognizes the need to explain both the ecological interdependency relationships and the basic conditions of individuation (Ruiz-Mirazo et al., 2004). However, when it comes to establishing a common basis of self-organization, the autonomous perspective limits itself to merely conceding the thermodynamic grounding in relation with the notion of constraint, without accepting the broader importance of thermodynamics and spontaneous ordering that have been advocated by the theories of self-organization (e.g. Salthe, 1985; Swenson, 1989; Kauffman, 1993).

2. Why Self-organization?

In Sections 1.2 and 1.3, I briefly addressed the theoretical approaches in so far as they could be alternatives to self-organization, or as they contribute to the theory of self-organization. Now, to complete this critical review, I will explain why self-organization is preferable to other theories within organizational approach. The following sections will also clarify in which ways self-organization in the ontogeny of the organism relates to the universal aspect of self-organization.

2.1 Self-organization between history-based and law-like explanations

In the first chapter, I addressed how the universal aspect of life is related to the transitional dynamics of self-organization on a thermodynamic basis. I have also mentioned the claim that considers spontaneous ordering as a fourth law of thermodynamics (Swenson, 2009). These two aspects, a history-based explanation in the former, and a law-like explanation in the latter, involve a crux of the issue of making sense of self-organization. On this issue, I argue that the universality of self-organization is not originated in a law of nature, but in its historicity, i.e. self-organization does not involve a certain nomological necessity by definition, but it can be universally associated with a gradual process of emergence and then persistence of adaptive systems in nature. Therefore, it would be better to accept the universal aspect of self-organization as a tendency for the creation of certain forms of causation such as interdependent networks and circular systems. This also involves an evolutionary dimension of increasing complexity (see Section 1.1), since these kinds of causal forms are expected to be viable in the long-term due to forming robust and flexible structures.

As I tried to show above, both autopoiesis and the autonomous perspective focus on what is unique in life's organization that underlies the autonomy of living systems. In contrast with the abovementioned approaches, self-organization is not a theory that begins from an abstract description of living systems, but from the potential of matter to create life. Self-organization differs also from the neo-Darwinian approach that is primarily focused on natural selection. In this sense, the attitude of seeking design properties of life independently from its material basis needs to be rectified by beginning from the history of life as the potential to form reciprocal linkages. The interpretation of the history of life is not only a matter of explaining adaptive traits based on random mutations, but also of explaining the emergence of viable forms based on the dynamics of organizational robustness. Life must be understood in terms of the emerging networks that are established by the contingent appearance of reciprocal causal relations. This potential by the dynamics of contingent reciprocity is a necessary condition, even if not a sufficient condition for the emergence of life.

With this regard, Kant's regulative account of self-organization focusing on the organism denotes the product of the underlying phenomenon, but not the phenomenon itself. Only transitional self-organization exposes the underlying spontaneous order, leading to the expansion of a global possibility space in which life had the opportunity to flourish. Thus, a unified theory of self-organization explains both the common aspects of organization and those that make life different from other kinds of organization. Moreover, it demonstrates the need to reconsider our understanding of causation and move away from the view that matter is fundamentally inert (Arshinov & Fuchs, 2003; Heylighen, 2010). Emergence of life is not an exception, but on the contrary, it is the approach of classical physics that led previous philosophers to think that it was, requiring appeals to an external factor or to a lucky coincidence. Life, as a culmination of self-sustaining order, is a possibility within the multiplicity of contingently formed reciprocities. Therefore, although self-organization is a universal principle, biological systems are at the heart of the problem.

This brings us to another problem, the likelihood of life as a consequence of the realization of matter's potential for organization. Is the emergence of life a matter that is to be primarily associated with a unique event that created a new possibility space of organization? Or, is it a consequence of the emergence potential in physico-chemical interactions that is repeatedly manifested, only unique in the sense that specific ways of evolvability and agency arise as a result of the accumulated effects of a global transformation that catalyses itself? Theories on life's organization are not usually dependent on exact preference between these two poles, but varies to different degrees across a spectrum: A theory approximates to the former inasmuch as it promotes the idea of life's relational novelty as a possible but improbable phenomenon, whereas it approximates to the latter inasmuch as it promotes the intertwined dynamics of emergence among living and non-living interactions. In this regard, approaches such as Jacques Monod's (1972) theory, which asserts the improbability of life, is quite close to the former pole of the spectrum, whereas Herbert Spencer's understanding of evolution and Vladimir I. Vernadsky's theoretical approach that considers the formation of biosphere as a natural (in the sense that it is likely) result of a geo-chemical transformation approximates the latter. This is because both Spencer and Vernadsky explain the individuation dynamics of organisms by appealing to a universal principle of self-organization. My position is that life's gradual development is quite probable considering that self-sustaining networks are likely to be maintained as an evolving global system. Not only life and its environment are coupled materially, but also living systems and global environment are organizationally coupled in the sense that spontaneous ordering characterizes reciprocal linkages between systems and their surroundings.

Vernadsky considered life as a global, interconnected phenomenon, which naturally emerged from chemical activities on Earth (Vernadsky & Margulis, 1998). According to this approach, not only are living systems interconnected, but also living and non-living matter are inseparable, forming a single self-sustaining global system. The biosphere has been formed through a geological transformation, as the activities of microorganisms and insects have led to the making of moist soil in which minerals circulate, allowing the growing of plants. In a similar vein, James Lovelock (1979/2000) pioneered an approach known as the Gaia hypothesis which argues that the biosphere is a self-regulating system as a whole. According to

Lovelock, physical conditions such as the temperature of the atmosphere and salinity of oceans are globally determined through life's activities. However, considering biosphere as a single evolving system, which I claimed to be a case of transitional self-organization, poses a problem in terms of the explanatory limits of the Darwinian theory. Natural selection operates only if there are multiple reproducing individuals in a population. Earth does not belong to a population of its kind, and biosphere as a whole population has no competitor. Therefore, natural selection does not apply to the evolution of biosphere as a whole (Dawkins, 1982). On the other hand, from the perspective of self-organization, evolution on Earth needs to be revised to the evolution of Earth (Swenson, 2010, p. 174; see Chapter 1), which implies an incongruity between Darwinian evolution and self-organization. The solution of this problem requires understanding self-organization as a historical phenomenon, which is an issue that I return below. But first, let me introduce another interpretation of the universal characteristic of self-organization which is considering self-organization as a law.

Formation of patterns appears in processes that are so different from each other, including biological phenomena such as the evolution of populations and the morphogenetic development of the embryo, as well as physical phenomena such as turbulence in fluid movement and fractals in geological structures. If all these cases are manifestations of self-organization, which I believe to be the case, this offers support to an understanding that self-organization is a universal principle. Both in chemical interactions such as autocatalytic systems, and non-chemical interactions due to kinetic factors such as convection cells and hurricanes, self-organization denotes the characteristic of a system in focus to act upon itself, pulling sources in the surroundings into the limits of its extension (Swenson, 2010, p. 170). We saw in the first chapter that on this basis, Swenson formulated a fourth law of thermodynamics, which presumes that a complex system will "choose" among different paths the one that maximises its entropy production. Is it really possible to formulate self-organization in this way? Let us ignore the potential disputes this raises specifically in relation to physics for one moment. Even if maximization of the entropy production is the case, it is hard to conclude that this principle is a law-like explanation of self-organization. Entropy maximization as a universal principle refers to a quantifiable aspect of organization, whereas I believe that universality of self-organization is basically a qualitative issue, which is based on a tendency for certain causal patterns always contextualized in a unique systemic condition. Thus, the qualitative uniqueness is incompatible with law-like definitions of causal relations. For example, in living systems, self-organization has to do with organizational robustness and formal stability of boundary conditions, for which entropy maximization does not offer any direct solution. Furthermore, entropy maximization depends on the specific thermodynamic condition that a decrease in local entropy is always compensated by a universal increase entropy (Swenson, 2010, p. 172). However, if the boundary conditions of a system are not sustainable, utilizing the potential in the surroundings of the system faster only leads it to dissipate earlier. Therefore, universality of self-organization cannot be merely dependent on the self-reinforcing nature of non-equilibrium systems. A turbulent movement, which is one of the cases of non-equilibrium state, is temporally restricted to a certain processual condition, so its routine occurrence is not capable of building organizational hierarchy by itself. Most of the self-reinforcing processes create temporary boundary conditions, and in fact, it is the relative stability of boundary conditions in Bénard cells that makes them observable, and hence, an exemplar of non-living self-organization. Contrary to Kauffman's (2000) early claim, spontaneously arising autocatalytic systems are hardly sustainable, which is why models find that only a continuous existence of an external food resource can restore their activity (see Chapter 1). Similarly, in a co-evolving system, there might emerge interdependency networks between cooperating species that give an evolutionary advantage to relevant members, thereby leading to an increase in rate that these networks take in external energy. But again, sustainability is a problem. A rapid growing of these networks would bring an evenly rapid depletion of the resources, and this would eventually lead to an ecological catastrophe for the system.[34]

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[34] All these objections towards the maximization of entropy production as a sufficient condition of self-organization is parallel with the fact that in most self-organizing processes, a positive feedback in the short term is coupled with a negative feedback in the long term.

I have previously explained how transitional self-organization is a tendency for structuration,[35] which makes possible the creation of higher levels of organization (see Chapter 3), such as: the integrity of cellular processes in a multicellular organism, collective behaviour in animal groups, or the complex interplay between ecological and evolutionary dynamics. Reciprocity of causal relations and the emergence of self-sustaining loops have a basic role in this. However, in relation to the long-term evolution of these systems, dynamics of spontaneous ordering is a necessary, but not a sufficient condition. These dynamics might contribute to the formation of patterns at a lower level available for functions at a higher level, or to qualitative leaps in the population dynamics, but they cannot be expressed as a law that alone provides the formula of the living systems. Instead, since living systems require dynamics of evolvability, the evolution of organisms as autonomous systems with stabilized boundaries refers to a quite inclusive issue of life as a whole system, and transitional dynamics are included in this historical phenomenon at different levels.

If self-organization is not a law of nature, how should we understand its global occurrence, then? This question requires going back to the historicity of self-organization that is mentioned afore. The basis of understanding self-organization as a universal principle should go beyond the false dilemma that the only alternative to the idea of inevitable progress is an arbitrary concatenation of several causes. In other words, self-organization does not have to be elevated to the status of a law of physics to support the argument for directional evolution. A solution to the dilemma between randomly aggregated evolutionary factors and a law-like explanation of self-organization involves considering self-organization as a phenomenon of evolving complexity that also includes biological evolution. This kind of understanding is reflected in Spencer's theory of evolution, which is closer to a view of universal self-organization that presumes a general increase of complexity due to internal relations of a system. Spencer's theory has fallen into disfavour over time, partly due to an overemphasis on the role of randomness in evolutionary theory. Paradoxically, it was Spencer who coined the notion of "the

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[35] For this notion, see Fuchs (2003).

survival of the fittest" (Spencer, 1898/2016) upon reading Darwin's *Origin*, which contributed to an overestimation of the role of natural selection as the single mechanism of evolution. This in turn has led to a notion that evolution is only a problem of multiplicity, since according to the principle of the survival of the fittest, driving power of evolution is now conceived a war of all against all. The abovementioned theoretical denial of the evolution of biosphere as a whole (Dawkins, 1982), hence any conception of directionality in evolution, is a consequence of this type of reduction to natural selection. On the other hand, this way of thinking neglects the role of cooperation, and in a broader context, the interconnectivity of the biological phenomena. This is evident from loose interconnections at all levels to symbiotic forms, niche construction, and several globally emergent situations in the ecological conditions that brought irreversible changes, e.g. the Great Oxygenation Event, which led most anaerobic organisms to extinction due to the increasing concentration of free oxygen in the atmosphere. In general, self-organization and natural selection are intertwined phenomena. The former involves the role of selected effects, which is described as selection among micro-configurations at the macro level (Haken, 2000; Swenson, 2010), and vice versa, the latter can be influenced by self-organization in different ways (see Chapter 1). Considering the evolution of life in the context of universal self-organization presents a strong case in favour of the directionality of evolution because sustainable networks can be selected against short-term adaptations, which enables a long-term tendency through evolution. All self-organized systems, just like evolving populations, involve both the elements of conflict and positive reciprocity among its elements. Alternative states of complex conflict-cooperation relationships form an infinite possibility area that is discovered through organized transformations. Even though it would be too ambitious to claim that self-organized end-state is inevitable, it is possible to think of a complex, flexible, and self-maintaining hyper-network as a likely outcome of an evolution, beginning with simplistic conditions, in which this end-state is a final cause. This suggests that global context of self-organization should be ascribed to directionality and irreversibility as a consequence of systemic changes, instead of a law-like conceptualization. The necessity due to self-organization is to be found in certain forms of self-maintaining systems imposing themselves through evolution, and therefore transitional self-organization is a historical tendency.

Finally, I will briefly consider how self-organization vis-à-vis natural selection relates to regulative self-organization of the individual (see Chapter 4 for details). Concerning the question of what makes an organism, natural selection focuses on the negative aspect of the explanation by focusing on the processes whether the organism is eliminated or not, whereas it does not deal with the generative processes of the form (Goodwin, 2001). This is in line with an externalist explanation of the function of each trait. However, self-regulation of the organism cannot be explained from an adaptationist viewpoint (Griffiths & Gray, 1994). On the contrary, regulative self-organization is a question of internal relationality, according to which organizational constraints determine the structure of organisms. More importantly, the organism is not a mediocre accumulation of adaptive traits, but it is the materialization of a process of lifespan development from birth till death.

In this section, I tried to demonstrate that self-organization has a universal aspect characterized by a tendency for the emergence of reciprocal relations. Self-organization does not need to depend on a law-like explanation in order to claim universality because its universality is originated in its historicity. Moreover, the constructive aspect due to emergent reciprocities support the idea of directionality in evolution, as the inclusive networks of biological organization is expected not only to be viable, but also to flourish in the long-term.

2.2 Circular causality

Below, I discuss the question of how the universal principle of self-organization is associated with the ontogeny, as it is essential to resolve this problem before examining the self-organization of the organism in the following chapters. This builds from an argument proposed in this chapter in support of the inclusiveness of the theory of self-organization compared to other approaches of life’s organization. This section offers further support to this argument by demonstrating the connection between the general aspects of causation and the specific understanding of the organism. The answer lies in the tension between circular causation, and any kind of perturbation that has the potential to disrupt, distort, or improve causal cycles. As the chaotic nature of things does not allow reaching stability by simple means, some additional mechanisms would be needed to tolerate the perturbations that interfere with causal cycles. This is why only living systems that have this capability can sustain cyclic processes in the face of irregularities. The circular nature of living processes is also conceded in alternative approaches, but it is only from the perspective of self-organization that it is acknowledged as a universal basis of emergence (Swenson & Turvey, 1991; Heylighen, 2010). From this perspective, causal cycles are expected to arise by themselves, and variation and selection among circular processes – which points to a general principle beyond natural selection – is the key to emergent order.

As pointed out before, the interdependency between parts within the organism is a strict form of reciprocity in which parts exist due to their dynamic relationships with other parts and the whole. On the other hand, an essential implication of transitional self-organization is a transformation from random associations of reciprocal relations to interdependent networks. The problem is, as a banal fact that has already been mentioned here as well as in other works, organisms cannot be formed spontaneously. Thus, there is an explanatory gap between a relation of contingent reciprocity and a highly self-constrained network of organization within the organism. A good strategy to overcome this deficiency is to consider this issue from the perspective of abiogenesis in order to retrodict possible pathways that began with the spontaneous emergence of autocatalytic networks. Another useful way to acknowledge the causal nature of life is to draw attention to the fact that contingent reciprocities have not been replaced, but they are still there within the organism, as moulded by selective pressure. These reciprocal relations are thereby embraced in a highly robust and complex regulative system of organization. The role of symbiotic encounters in the formation of complex living forms is striking in this sense. The engulfing of the first mitochondria by another bacteria cell is a contingent event. Yet, through the life cycles of the relevant bacteria species, contingently established reciprocity becomes the basis of a new structure. The interesting aspect of this example is that an event is transformed into a cyclic process through the machinery of reproduction. In other words, the event becomes structure. This is also evident in the activity of the bacteriophage. Considering that there has to be contingent beginnings of the life cycles of these parasitic viruses that initiated the copying of their chromosomes by using the bacterium host in a chance event, the question is at which point this type of event becomes a repetition as a manifestation of the reciprocity between the relevant genes coding the behaviour and behaviour reproducing the genes. Another similar example is the evolution of greenbeard genes that enable two individuals to reciprocate their altruistic behaviour between each other (Gardner & West, 2010). These examples would be enough to indicate the power of life cycles. Still, as these examples are all the consequences of evolutionary contingency (Beatty, 2006), they are dependent on the reproductive mechanism of life as a given. Thus, they cannot prove a natural relation between contingency and reciprocity because they are derivatives of life cycles instead of developments from scratch.

A more crucial question at this point is to ask, beyond life cycles, why life depends on cyclic processes. This is of such importance because cyclic processes are ubiquitous and fundamental in metabolic regulation and other aspects of living systems. A feedback loop is a common causal cycle that appears both in living and non-living systems. As to the latter, the Carnot cycle, which is the basic thermodynamic mechanism utilized by the first steam engines, consists of the circulation of heat between a hot and a cold reservoir. Through the cycle, heat is transformed into mechanical energy that enables the piston to move between the reservoirs. Causal cycles are so ubiquitous in biological systems that they constitute the basic condition of organization. Oxygen cycle is an example of circular processes at the ecological level. It is mostly determined by photosynthesis, which produces oxygen as a waste product, and respiration, in which oxygen is consumed. Photosynthesis and respiration are each cyclic processes in their own, too. In photosynthesis, carbon dioxide and water are combined into bigger molecules through the Calvin cycle, and in respiration, organic molecules such as carbohydrates are broken down to release energy through the Krebs cycle. In these processes, electrons are carried by the molecules such as ATP and NAD^+, which are also used to regenerate the biomolecules that are required to continue with the next cycle. As the cyclic regeneration also serves the extraction of energy from the materials involved, it enables the organism to stay far-from-equilibrium (Eigen & Schuster, 1977). Cognitive processes are considered as circular as well because there is a reciprocal coupling between perception and action that leads the organism to behave according to the environmental stimuli (Swenson & Turvey, 1991; Vernon, Lowe, Thill, & Ziemke, 2015). Furthermore, some other cognitive skills grounding human autonomy imply a detachment from sensory-motor coupling, but also the creation of a higher-level circularity as identity (Negru, 2016). These examples demonstrate that causal cycles are more pervasive than one realizes at first glance. This indicates how causal cycles can be understood as an essential feature of life, which should lead us to think about the emergence of this particular causal form that is necessary for the potential for life.

A simple causal cycle is a basic self-maintaining process. The logical relation between self-maintenance and circularity explains why this type of process is prevalent in nature. Once formed due to random interactions, a causal cycle is sustained better than any linear process. The linear process, by definition, lacks the condition of regenerating its current form. A causal loop could be considered as the simplest form that is capable of maintaining itself in a theoretical sense. In a hypothetical causal closure, the cycle would not require an external cause, as the repetition of the causal system would create its own order as an endless cycle. In this causal loop, repetition of the system is a routine, and while the loop fulfils its motion, there is no possibility for a transformation that could make a cycle different from previous ones, either.

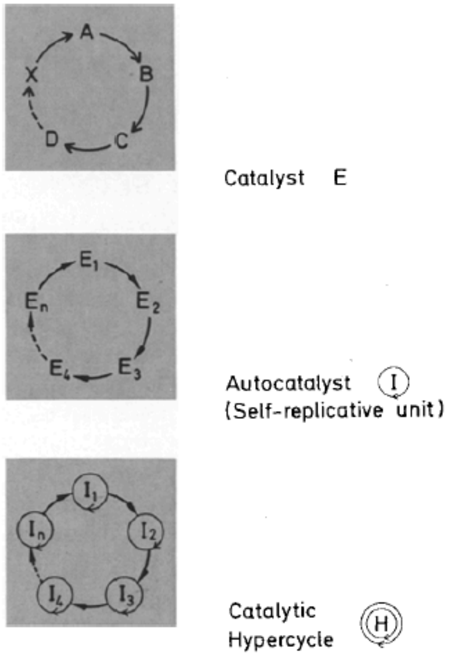

Figure 2.2 The hierarchy of hypercycles (from Eigen & Schuster, 1977, p. 546).

However, only in this kind of hypothetical system where there is neither loss of energy nor perturbations circular causality lacks the dynamics of self-organization. In real interactions, systems never appear as wholly isolated repetitions that are kept perfectly unchanged. Since even the solid matter slowly dissipates its kinetic energy, an energy input is needed to tolerate this energy loss. Moreover, perfect repetitions would not be the case in reality due to the principle of sensitive dependence to the initial conditions. This principle states that slight irregularities at any seemingly regular movement are amplified in time. Although chaotic behaviour is directly evident only in certain processes, physical systems are all subject to nonlinear dynamics. Thus, perturbations might seem ignorable in the short-term, but they would eventually end up with dramatic alterations in all physical systems (Bishop, 2016). This is why a real system cannot revert back to initial conditions. Therefore, in a system that is able to preserve its processual form, some other mechanisms are required in order to make the system robust against perturbations.

Inescapable perturbations entail a logical association between complexity and circular causality in self-organized systems. A simple causal cycle is weak in its self-preservation because it has no solution for the conditions that could disrupt its repetition. To be able to repeat itself, a system has to include some additional mechanisms beyond a simple causal cycle. This is why self-organization requires a certain level of complexity that involves tolerating micro-scale variability due to the macro-scale structure, and causal cycles in biological systems must possess a certain complexity that includes mechanisms to “repair” the decay into chaos. In this sense, self-organized processes include imperfect forms of circular causality, in which relations are arranged in a complex network instead of a single loop. Causal loops are widespread in nature, in self-organizing phenomena in particular. Yet, they are obviously not manifestations of a perfect form in the mentioned hypothetical condition, but a form that is realized as a mixture of irregularity and self-correcting repetitiveness. Hence, the imperfect circular causality can be put forward as one of the main elements of self-organization.

Eigen and Schuster (1977) developed an influential theory of life’s self-organization based on circular causality. They argue that only a cyclic model can explain the pre-Darwinian evolution of first biomolecules and the appearance of the first genetic code as a frozen accident. Their relevant model is named *hypercycle*. In the hypercycle, there is a stepwise process of chemical reactions in which every product is the reactant of the next step, and thereby the whole system becomes its own catalyst (Eigen & Schuster, 1977, pp. 542-543). Although a causal cycle is a diachronic chain, inasmuch as the system becomes complex, causal cycles might appear in the form of synchronized networks that include a spatial expansion of circularity. Based on this, Eigen and Schuster state that a hierarchy of cyclic processes can be formed in which self-catalysing cycles become the components of a higher order hypercycle (see *Figure 2.2*). They also argue that these autocatalytic cycles have their own variation and selection dynamics, which indicates that self-organized systems might be characterized by these principles beyond the scope of natural selection. On the one side, these systems are competitive units as any coupling between cycles leads to the exclusion of other possibilities. On the other side, competitive units can be turned into cooperating ones in the emergence of a higher order system that includes these units in a stabilized form (Eigen & Schuster, 1977, p. 546). As these systems are not traditional Darwinian individuals, their scheme of organization is in line with a viewpoint that self-sustaining reciprocal linkages and selected effects operate within a wider ground than natural selection.

Now that I have discussed how reciprocal relations in Darwinian evolution and in pre-Darwinian conditions lead to the creation of self-maintaining structures, the question remains regarding the universal basis of the emergence of cyclic processes. The answer lies in the ubiquity of attractor states in nature (see Chapter 1). As exemplified by Bénard cells, the emergence of an attractor from random interactions within a system proves how causal cycles are stabilized as a consequence of reciprocal linkages. There are different types of attractors that relate to life’s organization in different ways. For example, a strange attractor appears as an unpredictable, non-periodic, and semi-organized behaviour of a system that is mostly known by the swinging patterns of a hinged pendulum. It has been hypothesized that malignant tumour growth is an instantiation of a strange attractor, and a growing area of study has been focusing on the nonlinear basis of similar cellular processes (Nikolov, Wolkenhauer, & Vera, 2014). According to a similar claim, cancer is related to the emergence of specific attractors in genetic regulatory networks that divert the system from its normal parameters (Huang, Ernberg, & Kauffman, 2009). Another type of attractor that is essential for life's self-organization is the stable limit cycle, in which system moves into a periodic behaviour by tolerating any perturbations. Oscillators in living systems are either due to the limit cycle or induced by noise (Mitarai, Alon, & Jensen, 2013). For instance, the limit cycle is the basis of circadian clock oscillations (Lenz & Søgaard-Andersen, 2011), which I discuss in the fourth chapter in relation to the temporality of biological organization.

Conclusion

In this chapter, I discussed alternative approaches towards life's organization as well as early contributions to the ideas of self-organization. In many cases, autopoiesis is not in compliance with self-organization. Above all, the notion of closure, although being useful to highlight the basis of autonomy, is far from sufficiently describing life's fundamental condition which is ecological organization. In comparison with autopoiesis, the autonomous perspective is a step forward, as it identifies the thermodynamic basis of life. However, the autonomous perspective disregards the spontaneous dynamics of order in life, which leads it to presuppose a sharp distinction between self-organization and the regulation of autonomous living systems.

I also discussed how the universal basis of life's organization resides in cyclic processes and the emergent stability of the systems. Certain physical processes that are analysed with the models of self-organization such as robustness, criticality, and feedback loops arise in all kinds of natural systems including biological ones. Yet, pointing out the universal feature of self-organization does not imply that life's organization is reducible. New hierarchical dimensions arise with the increasing complexity that cannot be explained by any generalization of these underlying dynamics. In this sense, biological processes appear across an emergent dimension that is formed historically, and therefore it is not possible to reduce life's organization to a universal principle of self-organization. On the contrary, the universality of self-organization does not refer to a type of law-like necessity, but only identifies general trends, e.g. certain forms of reciprocal linkages tend to be sustained in self-maintaining structures. The latter is an explanation of selected effects, and therefore demonstrates that self-organization and selection are intertwined phenomena. Transformation from randomly established reciprocal relations to interdependency, which I termed transitional self-organization, is a pervasive phenomenon. The ubiquitous existence of these dynamics suggests that this type of patterns might have also been involved in the emergence of life, as we can expect the role of attractors in the transformation of Earth's physico-chemical conditions. This would mean that, contrary to Monod's (1972) claim, the emergence of life is not a miraculous event, but a likely possibility, as a consequence of the creation of order by self-organization.

This chapter has offered an account of the fundamental dynamics of a self-organizing system, "which is typically non-linear, because of circular or feedback relations between the components" (Heylighen, 2001). A system requires a certain variety of stability states to cope with environmental changes, and this is why self-organization is so fundamental for living systems. As will be explained in the following chapters, through self-organized processes, systems can discover novel ways of organization, which leads to the expansion of interdependent relations and construction of higher levels of organization. Therefore, life's evolution cannot be thought as distinct from self-organization.

Chapter Three

Levels of Organization in the Organism

Introduction

In this chapter, I explain the role of emergent dynamics of order in the formation of hierarchical levels of biological organization, before focusing on the problem of diachronic emergence in the next chapter. As noted in the previous chapters, bottom-up dynamics of self-organization are utilized in many ways, yet they are not sufficient to explain life's organization. This brings us to the main issues of this chapter, that is, levels of organization and downward causality. One way of approaching life's emergent organization is to trace the issue of hierarchy back to the origin of life, which involves the big question of how life began through chemical self-organization (Luisi, 2006; Eigen & Schuster, 2012), or to tackle questions such as the interaction between natural selection and self-organization (Swenson, 1989; Hogeweg, 2005). Although important, this chapter will not focus on the evolutionary aspect.[36] Many of the issues with biological self-organization emerge at the organism level, so I focus on the organizational levels within a modern multicellular organism. Specifically, this is the question of how emergent order is exploited across multiple levels of organization.[37]

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[36] This is also because this aspect involves a broad scientific topic in which answers relating to self-organization mostly depend on empirical studies. For instance, a new experiment on RNA world hypothesis might shed light to the relevant arguments concerning the evolutionary aspect of self-organization. This hypothesis on the origin of life asserts that RNA emerged before DNA in primitive cells. According to this idea, both the storage of hereditary information and catalysis of chemical reactions were carried out by RNA prior to the existence of DNA. In this sense, any revealing concerning this issue would also help to understand the evolutionary background of molecular self-organization.

[37] When it comes to the evolutionary basis of self-organization, it will suffice to note some of the hypothetical stances concerning how physical forces have been evolutionarily constrained through biological regulation (Newman, Forgacs, & Müller, 2003). From the historical perspective, the evolution of the multicellular life form is based on an ascending complexity. This does not mean that the direction of evolution always favours the complex over the simple. As Vrba and Gould (1986) have explained, even though hierarchy is historically built by the integration of simpler forms into more complex entities, this does not imply that selection always favours the complex against the

A core idea of this chapter is that a non-reductionist approach and a multi-scale analysis are necessary to understand the emergent dynamics of life. It would be a mistake to assume that a molecular-level analysis is sufficient to understand biological organization. This would perpetuate the tendency to reduce processes to molecular biology and generally undermine the value of macro-scale approach. Similarly, to explain biological organization by solely focusing on the bottom-up construction of order results a defective explanation that ignores the top-down context of biological functionality. Therefore, a more complete account of the organism's self-organization will be able to explain how emergent properties of the organism rely on several causal capacities. Biological form is acquired and dynamically maintained throughout the life cycle of the organism. This is the basic claim of epigenesis (see Chapter 2 and Chapter 4), which is defended against preformationism (Moss, 2003).

Below, I introduce an analysis concerning the integration of parts at multiple levels. This involves an examination of the dynamics of self-ordering, self-assembly, and pattern formation, since these are the main mechanisms which enable the formal stability of the organism. These dynamics denote systemic regularities utilized within the bottom-up construction of order. For instance, self-assembly of the bilayer at the molecular level becomes functional by forming the membrane at the cellular level. Spontaneous dynamics of order, biophysical capacities of cells and tissues, and combinatory potential due to the alternative functionality of a component in higher-level networks are among the bottom-up dynamics of organization. On the other hand, centralized functions such as the immune system could be considered as downward causes. Centralized mechanisms are processual networks of functions that make use of the rest of the organism as a potential source for reorganizing the system. In this context, the organism is a process of constant interplay between bottom-up and top-down dynamics. This provides the foundation for the next chapter which develops a potentiality approach in relation to the processual nature of the organism.

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simple. Nor does it imply that we should be seeking a deterministic law that requires an increase of global complexity in all circumstances. Instead, the appearance of lower-level dynamics is the prerequisite for the complex multicellular organism.

The relevance of emergent dynamics in the formation of organizational levels is evident within an expanding scientific literature that appeals to the concept of self-organization. The importance of self-organization is apparent from the increasing popularity of the notion, notwithstanding some inconsistencies that I detect with the definition (see Section 1.3). Self-organization has been traditionally referred to in the studies of embryo development (Deglincerti et al., 2016; Weiss, 1968; Wennekamp, Mesecke, Nédélec, & Hiiragi, 2013), whereas recently the concept is ever-increasingly deployed in different areas from cellular interactions to regulatory networks, to name a few: molecular self-assembly – or self-organization (Luisi, 2006; Vendruscolo, Zurdo, MacPhee, & Dobson, 2003), self-organization of organelles at the cellular level (Maly & Borisy, 2001; Misteli, 2001, 2009; Karsenti, 2008; Junkin, Leung, Whitman, Gregorio, & Wong, 2011), tissue self-organization (Kadoshima et al., 2013; Muguruma, Nishiyama, Kawakami, Hashimoto, & Sasai, 2015; Newman & Comper, 1990; Sasai, 2013), and self-organizing networks that operate in centralized functions (Pasquale, Massobrio, Bologna, Chiappalone, & Martinoia, 2008), such as the genetic circuits, the immune system (Atlan & Cohen, 2006), and the nervous system – including the brain's self-organization (Atasoy, Donnelly, & Pearson, 2016; de Gennes, 2007; Singh, Haobijam, Malik, Ishrat, & Singh, 2018). In the following sections, I address the understandings of self-organization across these levels also by discussing some of these studies.

First, I explain how bottom-up factors such as self-ordering dynamics at the cellular level help to create a basis for organization (Sections 1.1, 1.2, and 1.3). This requires discussing the nature of organizational hierarchy, which is context-dependent and open to interlevel causation. In this regard, I address the emergent dynamics at the molecular, cellular, and tissue level, which constitute the lower levels of organization within the organism. Some of the concepts proposed in this area also define certain research problems, e.g. dynamic instability as an intracellular mechanism, pattern formation in tissues, and morphogenesis in the development of the embryo. These phenomena all exemplify the emergence of ordered patterns through interactions at different levels, and therefore fall under the scope of self-organization. Non-equilibrium dynamics determine the *de novo* appearance of form within the cellular environment, and similar spontaneous factors are also relevant in tissue structures. Beyond these levels, metabolic activity keeps the organism far-from-equilibrium, as explained in previous chapters. These sections lay the foundations for understanding the association between metabolic dynamicity and lower-level spontaneity, hence it will be possible to see how the multicellular organism, as an evolved structure, exploits non-equilibrium dynamics at lower levels. Lower-level dynamics also indicate that self-ordering is inclusive of stochastic elements by its very nature. In fact, stochasticity might play a positive role in the emergent order, and therefore the elimination of contingency by an omnipresent regulation does not accurately portray the organism's organization. This supports my criticism of the mechanistic approach of autopoiesis in the preceding chapter.

The main questions examined in the rest of this chapter (Sections 2.1 and 2.2) are: how is the organism individuated and how does the system exert top-down control over its components inasmuch as the parts vis-à-vis the centralized networks are highly modifiable, replaceable, and dispensable? In this context, I emphasize the claim that centralized systems that are partially detached from intradependent processes of the organism act in complementarity with the causal capacity of spontaneous dynamics (Moreno & Mossio, 2015). Furthermore, the organism is not simply a composition of its parts, and sub-systemic elements are not perfectly integrated. Instead, the organism is a whole in which parts communicate with each other (Atlan & Cohen, 2006). Each of these points has been made in other studies due to considering the organism's activity as an open process. The novelty of my account is that it interprets these points from the broader perspective of the interplay between spontaneous dynamics and downward regulation. In this regard, the openness of the organismic processes also refers to them being unprecedented, and characterized by alternative realizations and even internal conflicts in certain circumstances.

1. Steps of Biological Complexity

In the following sections, I address general characteristics of hierarchical organization in the face of contingency, by emphasizing that organization is an issue beyond the composition of nested levels; I then explain how interlevel and intralevel dynamics of hierarchy are realized from the molecular to the tissue level. Lower-level dynamics of the organism are fundamental for the bottom-up construction of organization. This multiple-level analysis also demonstrates how new properties emerge beyond the micro-level determination of biological organization.

1.1 Hierarchy of the organization and contingency

It is the hierarchy of the organization that enables us to refer to higher vs. lower levels. However, the hierarchy has different implications depending on whether the context is material composition, organization, or cause-effect relations. In this section, first, I show why organizational hierarchy, which mostly determines the context of causal relations, is not simply a matter of material composition, and why we should focus on the dynamics of stability vis-à-vis contingent factors. Second, I remark that cause-effect relations within this hierarchy require a discussion of intralevel vs. interlevel causation. Finally, I explain why self-organization of the organism is not contradictory to the organizational hierarchy, despite some of the definitions of the former which consider it as a single level phenomenon.

According to a formulation that is based on material composition, a lower level denotes a part that is included in a more inclusive mechanism at a higher level (Craver & Bechtel, 2007). Within this mechanistic view, biological systems are hierarchical due to being nearly decomposable systems (see Chapter 4). According to this idea, living systems include intertwined mechanisms possessing stronger internal relations compared to those external to the mechanism (Simon, 1962). On the other hand, Craver (2007) states that this kind of mechanistic decomposition is relative to the function that is attributed to the mechanism, which implies the idea that organization depends on goal-directed processes that cannot be understood through static compositions. Although describing living systems as nearly decomposable can be useful for explaining their hierarchical nature, I will instead focus on the generic properties (see below and Section 2) of living systems, as understanding organizational hierarchy is an issue that extends beyond the mere description of compositional hierarchy.

Concerning the levels of organization within the organism, the received identification in contemporary scientific literature considers a hierarchy of molecular level, cellular level, tissue level and so on. For part-whole relations, this formulation merely denotes the compositional hierarchy of an entity. However, an approach beyond the part-whole relations of a single entity is necessary to account for the existence of organizational levels, because levels are only applicable when there is a class of individuals (DiFrisco, 2017a), e.g. we can speak of the molecular level only if there are multiple molecules, and based on that, there is the notion of molecule as a kind. A part-whole relationship that is exemplified by an individual molecule's involvement in an individual system is not sufficient to yield an explanation of the hierarchy of levels. Levels are described due to principles of organization with relation to entities belonging to certain classes. Parts constitute the whole in a specific entity, but both the part and the whole represent certain classes, which is a fact that enables an extension of the part-whole relation to a relationship between entities representing different levels. Therefore, beyond an individual part-whole relation, the hierarchy of levels depends on a generic understanding of living systems that concerns classes of individuals. For example, a specific cell being a part of a specific tissue, if considered only in the context of an individual animal's body, is basically a matter of material composition, whereas cells belonging to tissues in general is a matter of cells belonging to a lower level and tissues belonging to a higher level.

Understanding the hierarchical levels in the context of the individuals' association with classes is essential to identify specific organizational properties that are common to organisms. For instance, it would be quite difficult to say whether some properties are either contingent and unique, or generic and organizational, only by looking into the properties of a single tissue. Instead, an investigation of tissues as a class makes it possible to understand these relational properties as intralevel dynamics that are specific to a certain level of organization.

At this point, the following question should be asked: is it only the levels of scale, e.g. the molecular interactions at the micro-scale, that justify the attribution to different levels, or is it possible to make reference to specific organizational properties for these different scales? That is, what properties, if any, make a tissue something classifiable as a level of organization? As mentioned above, organizational levels are dependent on typical partitions of a whole, which indicates that the main issue extends beyond an understanding due to decomposing a whole as a unique individual (DiFrisco, 2017a). However, the properties that make a tissue a member of a class cannot be investigated through ideal token-type relationships. This is because the aspect of uniqueness cannot be discarded when investigating organizational types. Since a real tissue, for example, has always some degree of uniqueness, epithelial tissues of two different organisms are never identical, even though these individuals are homozygous. This is due to several factors of internal contingency, such as stochasticity in epigenetic mechanisms, signalling cascades, and gene expression, or environmental noise, which refers to the external aspect of the contingency (Bateson et al., 2001). As a consequence of contingency, there is no exact similarity between the members of organizational types.

One could argue from this that associating tissues or cells with certain levels of organization is a matter of convention, and that there is no ontological ground to assume certain organizational properties for different levels because there is no typical hierarchy that is applicable to all living systems. This objection would be against the typical partition of organizational properties. Since biological systems are characterised by diversity and contingency, it is not possible to establish neat classifications. A tissue is an ensemble of similar cells, but it seems difficult to come up with more specific characterizations that are generalizable to all tissues due to the diversity of biological entities. For instance, claiming that a membrane constitutes the closure of any cell including a nucleus, even though typical to eukaryotic cells, is not generalizable, as in the case of muscle cells there are several nuclei within a membrane. In this sense, there is a constant antagonistic relation between the contingently diversifying and the typically appearing features of the organization.

The contingent and unique nature of interactions within the part-whole relations poses a problem in terms of organizational types. The problem is twofold: first, it is about understanding the ontological basis of organizational types; second, it is about explaining why the factors of contingency do not lead to complete chaos by rendering any organizational classification impossible. This is important for understanding the actual reciprocal relations that keep tissues intact and provide the stability of developmental trajectories. Certain organizational patterns appear both spatially and temporally, even though each individual organism exhibits a unique trajectory of development. At the individual level, it might be the case that two members of a certain species are characterized by the factors of internal and external stochasticity, yet both still have the same types of cells, tissues, and organs, and thus both of them sustain their life as the members of the same species.

A gene-centred explanation would make the claim that these two individuals are members of the same species because both include genomes that are peculiar to that species. This claim is partially true in so far as it explains the similarity at the level of the individual, but it does not offer a full causal explanation for why there are similar organizational properties at lower levels. In other words, genetic similarity does not give an ultimate answer to the fact that the organizational nature at the molecular, cellular, and tissue levels is mostly immune to developmental contingency, as a consequence of which a certain amount of diversity among individuals co-exists with organizational stability. Neither does it account for why these organizational properties are widely shared across the phylum; that is, certain structural properties stay the same despite the variations due to evolutionary contingency. Therefore, an account of hierarchy which explains the emergence of certain organizational constraints through multiple levels is needed. As will be shown below, nested layers of organization are characterized by certain generic properties that are highly intertwined with the physical basis of biological systems. Contingent factors must be tolerated in certain ways due to physical necessities such as the requirement of keeping entropy low, or biological necessities such as supressing microorganisms and cancerous cells. Thus, an explanation of the organism must include the underlying reasons for the emergence of typical organizational patterns.

The hierarchy of organization also has implications in terms of cause-effect relations between the levels. As the self-organization of the organism is not a one-dimensional integration, a presumption concerning the lateral versus vertical nature of causal interactions is essential. Within intralevel interactions, spontaneous order, such as in the dynamics that keep a tissue intact and immiscible, is highly efficient. Concerning the molecules, cells, and tissues, some of the organizational properties are typical in the sense that certain types of spontaneous order, regulatory networks, or geometrical shapes appear with them. For example, a cell is typically (but not always) a unit characterized by membrane closure, and a tissue is typically an immiscible, semi-fluid structure with a certain geometrical shape such as a layer or a fibrous structure. In this sense, a level of organization is associated with specific dynamics of order usually led by the characteristic appearance of intralevel causation at that scale. Intralevel causation is based on structurally (though usually not productively) interdependent parts that belong to a lower level, as in the cells forming a tissue. Since the emergent dynamics are fundamentally realized as localized order, emergent properties are due to intralevel synergy exerting influence at a higher level.

An interlevel interaction appears when a mechanism at one level intervenes at a different level, or when higher-level structures determine a context for micro-scale interactions. An example of the former is cellular apoptosis, in which the body sends the cell a signal to trigger the self-destruction of the cell. On the other hand, the organizational context due to a higher level is usually based on the presence of the surrounding conditions facilitating a lower-level interaction. For example, protein folding is a process of thermodynamic stability, which is determined by intralevel interactions due to size (if the complexification from primary to tertiary structures is disregarded), but it is the cellular environment that enables protein folding. Similarly, a cellular membrane is crucial for maintaining the chemical processes within the cell, but more inclusive factors such as the interactions through the intercellular matrix also exert a large influence on the cellular function (Moss, 2003). Tissue cells are unified through the morphogenetic dynamics of attachment, yet tissues are functional thanks to the ongoing metabolic activity of the organism. In the end, this multi-level organization is hierarchical because the whole organism with its array of bodily functions is integrated by forming a top-down control over its parts. Nevertheless, this is not a strict causal hierarchy of top-down control because the interactions at a lower level might also influence a higher level. The elements of stochasticity at a lower level can percolate, or, due to some mechanisms that were mentioned in the previous chapters, get amplified into higher levels, which mitigates the downward hierarchy. For instance, this is evident with a point mutation's rare influence on a phenotypic property. In general, a point mutation does not lead to a phenotypic change due to the robust nature of organization, whereas in certain loci, a mutation might be expressed as a shift between the phenotypic traits, as in the example of a mutation that changes the eye colour of a fruit fly. It is argued that some point mutations of this kind could be even realized as an amplification of indeterminacy at the molecular level which is manifest at the population level when the point mutation is fixed through random fluctuations (Brandon & Carson, 1996).

Let us consider the other relevant factor for this discussion, centralized systems. The multicellular organism is a self-organized whole that includes centralized mechanisms exerting top-down control over the body. The role of the organizational hierarchy is usually not a disputed claim, whereas ascription to self-organization is. Since self-organization is usually associated with decentralized systems (Seeley, 2002; Camazine et al., 2003), mentioning hierarchical organization and self-organization together seems contradictory at first glance. Yet, I argue that in spite of this seeming contradiction, self-organization and organizational hierarchy are co-existent. Not only organisms, but all self-organized systems are organizationally hierarchical. This is due to an asymmetry in the interactions that determine the self-organized nature of a system. As shown in the previous chapters, self-organization denotes the fact that the relevant system is individuated as a whole by its organization. In this individuation process, the interactions that play a role in the cohesion of the system are distributed all over the system. This might lead some to think that self-organization is one-dimensional. Moreover, as self-organization is usually associated with the bottom-up emergence of properties, or distributed control through lateral relations within the same level (Shen, Will, Galstyan, & Chuong, 2004), this might support the misconception that self-organization contradicts organizational hierarchy.

However, the misconception here results from overlooking the dialectical aspect of the issue: Self-organization is a process that either changes the characteristics of a system, or adds new characteristics. Homogeneous turns into heterogeneous, and non-hierarchical turns into hierarchical due to transitional self-organization. Moreover, the distinction between transitional and regulative dynamics that was discussed in the first chapter deals with any possible vagueness in this dialectic, hence the emergence versus the continuity of the hierarchy can be distinguished from each other. In transitional self-organization, it is the local contingency that is caught up by the emerging pattern within the system, whereas in regulative self-organization, lower-level spontaneity is consistently integrated within the system. In both of these types, a notion of distributed or one-dimensional nature corresponds to an initial or a basic condition, since this one-dimensionality corresponds to causal symmetry and homogeneity. In actual fact, self-organization denotes the loss of one-dimensionality: Certain cases of transitional self-organization are characterized by the bifurcation process that creates a causal asymmetry within the system, which implies that specific interactions become more influential, or even dominate the system (Prigogine & Stengers, 1984/2017). In transitional self-organization, this is the appearance of hierarchy through an individuated process, whereas in regulative self-organization, individuation corresponds to functional integration in which hierarchy is characterized by multiple processes that could become dominant depending on the context of the functional requirement. In either case, contrary to the common misconception that self-organization relates to one-dimensional wholes, spontaneous emergence of order does not rule out the fact that some localized regions or certain causal cycles within these interactions are more influential than the rest of the system. In the paradigm cases of transitional self-organization, such as Bénard cell formation and ferromagnetic synchronization, certain patterns eventually dominate the whole, that is, an emerging hierarchy is what transforms the system.

In terms of hierarchy, regulative self-organization of the organism is not an exception, but rather represents a qualitative difference, as this type of organization is a much more complex case of asymmetrical individuation. For example, a human individual, as an organism, is self-organized. Yet, it is also obvious that there is a structural and organizational hierarchy in this self-organized structure, e.g. the neural cortex has a centralized role in cognitive abilities such as analytical thinking. Similarly, even though hormone regulation depends on the negative feedback control that is distributed over the human body, this does not negate the fact that the hypothalamus is a centralized region of the endocrine system. Centralized control mechanisms and regulative networks are integrated through specific goal-directed processes. As in the case of hormonal regulation, the system conditions and is also conditioned by the homeostatic control. Therefore, the hierarchy that results in the form of centralized networks is not in conflict with, but on the contrary, is essential for the organism's regulative self-organization.

1.2 Organization at the molecular level

The emergence of order in molecular processes has been investigated in several ways within different areas of study, such as non-equilibrium systems, artificial chemistry, and synthetic life. Although diverging both in method and basic research problems, these research fields are linked in terms of demonstrating that organic matter is not inert. The capacity to assemble is the most essential aspect of molecular dynamicity, and in the organization of the organism, this spontaneous capacity is utilized. A basic example of this capacity is the processes of polymer organization (Bucknall & Anderson, 2003). In this section, I examine the molecular level dynamics behind the organization of polymers. Biological form at this level emerges, above all, due to the thermodynamic and kinetic basis of stability. Basic forms of stereoregularity (see below) develop due to equilibrium conditions, that is, thermodynamic control, whereas kinetic control creates a temporary deviation from the equilibrium. One aspect of life's exploitation of the spontaneous potential for order is self-assembly that occurs by approaching the thermodynamically favoured state without using any external source of energy, although this is not a case of transitional self-organization due to far-from-equilibrium conditions. Then, I discuss the role of stochasticity in protein folding in order to show that kinetic dynamics are not mechanistically precise, but multiply realizable. This is an important aspect in terms of providing an alternative account of emergent dynamics. The interactions at the molecular level indicate that patterns might emerge due to kinetic factors.

Some of the concepts that are used to define organization at the molecular level are controversial. The most common cases of structuration at this level are self-ordering and self-assembly. Self-ordering refers to the capacity of molecules to form stereoregular shapes, such as spherically formed micelles (Abel & Trevors, 2006), whereas self-assembly refers to the more basic capacity of molecules to accumulate in water (Vendruscolo et al., 2003). On the other hand, conceptual demarcations between self-ordering and self-organization are disputed. Self-ordering seems to be a common way of referring to molecular regularity. In some studies, the emergence of molecular order is associated with self-organization (Luisi, 2006), whereas this kind of usage is criticized by other authors (Abel & Trevors, 2006). Restricting the application of the concept of self-organization to the individual organization of a system appeals to the dynamics that I associated with regulative self-organization. In this context, it is only a whole that can have the capacity to organize itself autonomously. Bottom-up construction of order at the molecular level only partially contributes to the constitution of self, which is why molecules, despite being characterized by a causal capacity to become ordered or assembled, cannot organize by themselves (see Section 1.3). Another problem of demarcation concerns the notions of self-assembly and self-organization. According to one of the proposals for distinguishing them, the former is simply a physical integration in equilibrium conditions, whereas the latter depends on far-from-equilibrium conditions (Misteli, 2001). This aims to distinguish far-from-equilibrium conditions (as in the constant dynamism of the metabolic function) from the formation of structure at equilibrium (as in the formation of phospholipid bilayer, see below). In that regard, I agree with the necessity of making a distinction between equilibrium and non-equilibrium processes. However, when it is proposed that all the non-equilibrium interactions should be referred to as self-organization in general, it seems that a possible misconception is to attribute the capacity to self-organize to the parts of a regulated system. To avoid this misconception, it is necessary to clarify the implications of individuation.

One of the most important factors at molecular level is the spontaneous formation of phospholipid bilayers and micelles, which are crucial for cellular compartmentalization where the chemical activities necessary for the emergence of life occur. The phospholipid bilayer denotes the molecular structure of the cellular membrane, and the micelle, which has a spherical structure, is thought to be essential for the formation of protocells in the beginning of life (Luisi, 2006). Most organic molecules form stable, crystalline structures in aquatic conditions, which are vital for life. These processes are, above all, due to the hydrophobic vs. hydrophilic behaviour of the different parts of a compound in an aqueous environment. For example, lipid molecules, which include a hydrophilic head and a hydrophobic tail, form phospholipid layers due to this dichotomous way of interacting with water. Hydrophilic heads interact with water molecules, and hydrophobic tails interact with each other, forming the inner part of the bilayer sheet (see *Figure 3.1a*). Similarly, linear backbones of amino acid chains spontaneously fold into three-dimensional protein structures due to the molecular bonds between the atoms of the side chain. Here, spontaneous folding refers to the fact that the relevant process is thermodynamically favourable. As mentioned above, the formation of stable molecular structures of life is usually due to thermodynamic stability. It follows that these molecular structures spontaneously arise as a consequence of the energy flow from a higher energy state towards a lower state. Thermodynamic stability might even be sufficient to keep viruses intact. Some viruses such as tobacco mosaic virus, after being denatured, can reassemble spontaneously upon the required conditions of their stability (Luisi, 2006, p. 105).[38]

The other essential dynamic at the molecular level is kinetic control. Kinetic control is based on short-term effects depending on specific interactions at a given moment, which is influenced by the statistically expected homogeneity in the long-term due to thermodynamic control, but results in localized dynamics that are crucial for the order of life. For example, chemical reactions occurring at a faster rate or requiring lower activation energy are kinetically preferred over those

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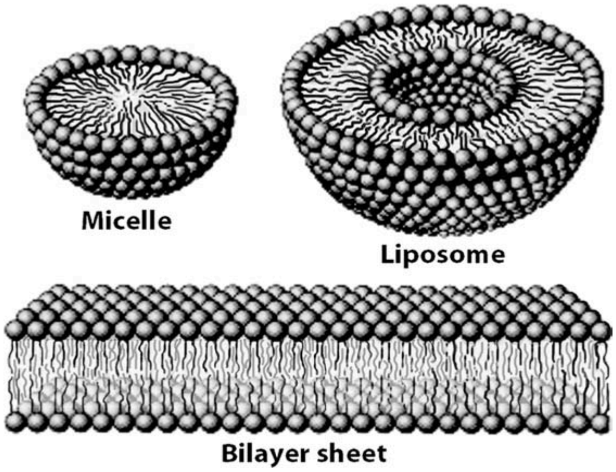
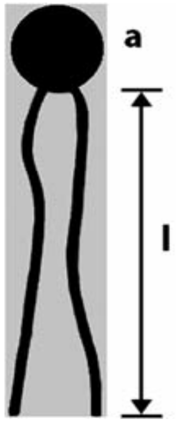
[38] The spontaneous ordering of the molecules should not be confused with the spontaneous formation of life. The problem of the origin of life, yet to be solved, requires several factors, both spontaneous and non-spontaneous. On the other hand, the self-ordering of the first molecules of life, especially that of amino acids has a crucial role in theories of the origin of life. This is due to the fact that amino acids can form spontaneously in nature. The famous Stanley-Miller experiment was successful in producing some of the amino acids from inorganic matter. Also, it is found that most asteroids include amino acid molecules, suggesting that spontaneous formation of amino acids is widespread in the universe.

occurring at a lower rate or requiring higher activation energy, even if the latter are thermodynamically more stable. In some cases, this determines the ultimate path of the chemical reactions because the reactions that are under kinetic control are sometimes irreversible. A prominent example of this is enzymatic activity. As is known, enzymes catalyse chemical reactions by affecting the kinetic conditions, such as enabling the collision of the molecules involved in a reaction. Thus, kinetic factors are those due to the relations between the molecules in specific configurations, e.g. an attachment between molecules keeping them away from equilibrium for a while. In other words, thermodynamics relates to the statistical characteristics of the energy flow, as the energy flow and the speed of each molecule become more homogenous in time. Whereas kinetic factors relate to the interactions as they occur through actual pathways. Thus, kinetic factors can sometimes sustain a heterogeneous condition, or create localized order as a non-equilibrium condition (Luisi, 2006).

The phospholipid bilayer formation is realized due to thermodynamic flow. The bilayer is the material of cellular membranes, and other forms such as micelles and reverse micelles are thought to constitute the first compartments of life in which autopoietic cycles evolved (Luisi, 2006). Physical properties of the molecules



3.1 a



3.1 b

Figure 3.1a Self-assembly of phospholipid structures in aqueous solution. Hydrophobic tails and hydrophilic heads lead to layered structures (from Luisi 2006, p. 183). *Figure 3.1b* Phospholipid forms differentiate partially depending on the ratio between *V* and *a* x *l* (from Luisi, 2006, p. 186).

depending on the ratios of the amounts of components directly influence which shapes will be formed (see *Figure 3.1b*). Micelles and bilayers are thermodynamically stable, whereas in other molecular structures such as vesicles, thermodynamic and kinetic control co-determine the form of organization. This implies that these macromolecules are kinetically trapped in a thermodynamically favourable condition as a lower energy state, which is nevertheless not an ideal condition corresponding to the lowest energy state (Luisi, 2006, p. 201). One of the crucial consequences of this combined function is the role of some molecular templates, which can distort the pathway to create specific regular molecular shapes. These molecules are then trapped in this form even after the agent that acted as a template is removed (Luisi, 2006).

Thermodynamic stability is the most essential factor at the molecular level. However, it is now more widely acknowledged that multiply realizable pathways in these processes are the key to the formation of macromolecules. This implies that a certain state of a phase transition, or even certain functions, can be reached by multiple routes converging at certain functionality. In this way, the stochasticity of the processes is utilized to create form, e.g. in protein folding, or in the production of immune cells (see Section 2.1). This provides a basis for emergent order, which is why the distinction of thermodynamic vs. kinetic control in isolation is not sufficient to explain the nature of these molecular processes. Take the example of protein folding: contrary to phospholipid bilayer formation, protein folding cannot be explained merely by self-assembly, and as a consequence, more sophisticated models have been developed in this area. In the past, the folding of the polypeptides into a highly complex functional protein within a short duration (up to a few microseconds) was considered a paradoxical case. Due to the huge number of possible conformations for a protein, it was previously believed that reaching the final state by randomly searching between these kinetic conformations should take a much longer duration than that observed (Levinthal, 1968). An initial hypothesis for the solution of this paradox involved the idea that some intermediates must be guiding the folding process, yet “now it is evident that folding must be thought of as a stochastic process in which the free energy is minimized through the exploration of a very conformational space” (Vendruscolo et al., 2003, p. 1209). This suggests that the formation of a three-dimensional protein shape is not led by one single path, but through a multiply realizable pathway that involves both the kinetic and thermodynamic factors.

Stochastically driven protein folding also has implications for interlevel causation. For instance, even though the mainstream view considers the amino acid chain as the code for specific proteins, this way of formulating of the issue might lead to the misconception that the code is a predetermining element and the protein shape is a passive outcome. In fact, the actual organizational context suggests quite the contrary, since “the folding is also coupled to a vast array of other events in the cells, ranging from the trafficking of molecules to specific environments to the control and regulation of the cell cycle and cell growth” and “unfolded or partly folded proteins may be involved in other functions such as translocation across membranes” (Vendruscolo et al., 2003, p. 1210). This reveals an interesting relation between regulation at the organism level and spontaneous order at the molecular level, which also demonstrates the interplay between bottom-up and top-down dynamics of individuation. According to this interplay, the molecular dynamics of order create the part, but it is the context of organization that enables the part to be utilized. Thus, these parts are analogous to puzzle pieces that are used in different combinations, depending on the functional requirement. The phase transitions in protein folding does not occur due to precise pathways, but due to folding domains, as “it appears that natural sequences are designed not just to enable the desired fold to be obtained efficiently, but also to minimize the possibility of the formation of alternative folds” (Vendruscolo et al., 2003, p. 1213). On the other hand, malfunction due to stochasticity seems to be the inescapable cost of the contingency that is fundamental for regulative organization. For example, misfolding of the proteins is a side effect of the stochasticity of protein folding, and diseases such as “Alzheimer, Creutzfeldt-Jakob's disease, adult-onset diabetes, cystic fibrosis, and many forms of cancer” arise as a consequence of this (Vendruscolo et al., 2003, p. 1210).

The fact that molecular processes are realized through a possibility space indicates that biological order is not an issue that can be approached from a calculationist viewpoint. Similar to the pre-deterministic conception of the protein formation, a mainstream approach posits that the genetic code is implemented through mechanistically precise pathways, while it is becoming obvious in contemporary biology that the notion of genes as the blueprints of organization does not correspond to an efficient mechanism vis-à-vis regulative self-organization. In the latter, basic causal processes are instead the feedback loops, stochastic transitions, and editing mechanisms, which in turn act upon the gene expression in a context-dependent way. All these molecular processes are regulated within the self-organized body through an open pathway.

A last point in this section concerns the context-dependency of the emergent dynamics at a molecular level. This point explains only one side of the interplay between bottom-up and top-down characteristics of self-organization. Processes such as self-ordering partially explain more complicated processes such as protein folding, as is evident from the fact that the three-dimensional shape of the protein does not survive for a long time out of the body. Without the whole regulative body, the capacity of spontaneous dynamics to sustain functionality is significantly restricted. This is supported by several experiments demonstrating that the molecules of the organism, unlike some alternative macromolecules that are created in synthetic biology, are very fragile in vitro. This is in line with the presumption that spontaneous order at the molecular level and regulatory networks at the individual level complement each other. For example, proteins fold mostly due to thermodynamic stability, but the process is enabled and accelerated because the relevant cells provide an aqueous environment with the required pH level. Moreover, even if some molecular forms such as the phospholipid bilayer can be formed independently from the organism’s regulation, the potential of thermodynamic stability is utilized in the right context through the regulation of the system. At this point, the holistic aspect of regulation in which higher levels constitute the surrounding conditions and the context of lower-level interactions is crucial. For example, self-accumulation is useful in many cases. Yet, it can also be harmful for protein functionality, and therefore some other regulatory mechanisms that prevent the accumulation are necessary in some cases (Vendruscolo et al., 2003).

Spontaneously formed functionality in equilibrium dynamics is a basic source of order, but in addition to this, a vast possibility area of the molecular interactions is investigated within kinematics, which requires taking into account the aspects of stochasticity and context-dependency. This requires a revision of the central ideas related to thermodynamics, which is a theory that was initially developed based on non-living systems. Due to the second law that presumes the increase of entropy, a thermodynamically favoured state is considered as equivalent to the micro-state disorder. However, it is evident from the formation of the phospholipid bilayer that a low-energy state can also serve to create molecular stereoregularity, whose contribution to biological order is to be appreciated only by considering the bilayer as a potential for the cellular membrane. Therefore, emerging order at the molecular level is only functional when it is rightly contextualized within the milieu of higher-level organization, and a thermodynamic definition of order and disorder might not be reflective of the specific situations of biological functionality.

1.3 Organization at the cellular and tissue levels

In this section, I focus on the dynamics of order at the cellular and tissue levels. The reason for the specific focus on these lower levels is their role in local dynamics of order: Lower-level dynamics provide a basis for individuality, as they are utilized by centralized elements that perform interventions across these levels. In this sense, considering the complexity of a multicellular organism, which is the main focus of this work, the dynamics associated with cellular and tissue levels are responsible for the local order, and these dynamics are finalized at the organism level due to the strict interdependency between parts. Moreover, morphogenetic factors of pattern formation are essential at this scale of organization, which demonstrates that the dynamics of spontaneous order and regulation determine the form together.

The generation of the form is an old problem of biology. D’Arcy Wentworth Thompson’s classic study, *On Growth and Form* (1942/2014), focused on the question of how the biological form is physically determined from a geometrical perspective. Many living things exhibit this structural regularity such as the phyllotactic arrangement in plants, logarithmic spirals in some of the shells, twisted form of a ram's horn, and the common egg shape in most of the egg-laying species. Thompson aimed to find the underlying pattern of this kind of regularity, and contrary to the Darwinian approach that emphasized the role of selection,[39] he thought that the patterns are the result of certain physical pathways through development and growth that basically determined the morphological properties.

Thompson's (1942/2014) research suggests that certain typologies in biology emerge as a consequence of certain physical constraints.[40] Of course, the growth of the organism is already a physical process, since the organism is made of the same elements as the rest of the world. Yet, Thompson's work is based on a deeper connection, as he develops an argument for the naturalistic appearance of the types of organisms. Just as several physical factors coalescing together produce certain landscape patterns, or the atmospheric events lead to the creation of snowflakes exhibiting crystal types such as the six edged stellar, certain physical processes lead to the formation of biological types.

The generation of biological form is a highly complex process that is now investigated from several approaches, namely, mechano-chemical interactions in the development of an embryo, gene expression, epigenetic regulation, responses to the environmental cues, etc., which are all the factors that are fundamentally related to development and growth. Hence, Thompson's theoretical framework of biological form is not completely obsolete in contemporary research, but rather has diversified through these approaches by creating new research topics such as morphogenesis and pattern formation. Concerning the formation of patterns, in a quite similar manner to Thompson, researchers investigate phenomena such as the eyespot pigment patterns appearing on the wings of some butterfly species or veneration patterns in the fruit fly wings (Urdy, 2012).

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[39] Thompson believed that the role of natural selection is limited, whereas Darwin did accept the role of form in generating elements. In any case, here the main difference between Thompson and Darwin is reducible to their alternative emphases on different mechanisms as an explanation of morphological traits (Gould, 1971; Kauffman, 1993).

[40] Kauffman (1993) claims that the modern study of self-organization is a return to this typological way of thinking. With a difference, Thompson remarked on the role of physical factors even as an alternative to the role of selection, whereas Kauffman incorporated natural selection into the theory of self-organization. According to this synthesis, the former occurs between the typological forms that are generated due to the latter. In fact, Thompson is referred to as one of the pioneers of the theory of self-organization, too (Bonner, 1996; Urdy, 2012; Bozorgmehr, 2014).

Contemporary formulations of these research problems focus on the formation of certain non-uniform structures, i.e., how certain physical transformations lead to the appearance of certain biological patterns as a consequence of mechanical and chemical factors. A shift in modern research has resulted in a deeper consideration of the role of regulation, that is, the question of how the holistic control of the organism influences the form. In this regard, the formation of patterns due to mechanical and chemical dynamics and regulatory networks are strictly integrated in so far as it is hard to analyse them separately. This offers strong support to the need for approaching this issue from the perspective of organizational levels to contextualize the problem of biological pattern formation and local dynamics of order. At the individual level, the interconnected networks characterize regulation, whereas at lower levels, regulation is accompanied by the spontaneous dynamics, e.g. tissue structure that is kept intact as a semi-fluid body or the immiscibility of the cells belonging to different tissues (Newman & Comper, 1990). These are the dynamics that are local in so far as they do not necessarily depend on, but contribute to the centralized organization of the whole. Contrary to the temporal multicellularity of *Dictyostelium discoideum* that was previously discussed, the typical multicellular organism can survive only when it remains as a whole or least inasmuch as it has the ability to regenerate its parts. This suggests that there is a reciprocal relationship between localized dynamics of order and the centralized function, as holistic integration is necessary to sustain full functionality in multicellular organisms. Within this reciprocity, the parts are morphologically integrated but each part on its own is stripped of the capacity to self-maintain as an autonomous individual. Thus, the localized dynamics are formatively determinant, but not fully determined by regulation because the infrastructural reciprocity of the lower-level patterns and processes are partial integrities that are already comprised in biological materiality, and reciprocity at the lower levels exists without any necessary interlevel causation triggered by homeostatic interventions. This does not ignore the fact that the viability of cells and tissues are dependent on constant functionality. What must be emphasized is that patterns and reciprocities at lower levels might be associated with multiple functions in different ways, however they are not necessarily involved in the particular material composition of a single functional structure because, as I will demonstrate in the rest of this work, a lower-level part is usually utilized in multiple ways.

Lower levels of organization are essential for inquiring into the physical emergence of order. In this context, some of the problems at these levels are as follows: What is the relationship between cellular form and the organization at this level (partially dealt with in relation to membrane structure in the previous section)? How should downward causality be understood at tissue level, that is, how efficiently do the emergent properties at the tissue level, such as the ones that are due to tissue geometry and positional information (see below), act on the function of the cells as parts? How does the pattern, in other words, the heterogeneous form, emerge from a relatively uniform structure through embryo development? These kind of questions have not been answered completely, which indicates that a physicalist understanding of the organism is still an unsolved issue. Below, I will explore some proposed solutions to this problem in the context of their relation to self-organization.

Let me begin with the cellular level organization. In cell biology, the concept of self-organization is often mentioned to denote the process of dynamic instability, which leads to the formation of certain organelle structures. A paradigm case is the processual nature of microtubules in their constant integration and disintegration. Microtubules constitute the cytoskeleton, and this dynamic nature enables them to govern cellular processes such as cellular division. Beside the cytoskeleton, nuclei and Golgi are other examples of organelles that are structurally formed based on dynamic instability. For example, the Golgi complex is responsible for packing proteins into membrane that has budded from the endoplasmic reticulum, and on this basis, it is claimed to be self-organized (Misteli, 2001). Indeed, Golgi is not a solid structure that can be understood as distinct from its function, but it is the integration of materials through a network in which membranes are delivered, as the continuous influx between the endoplasmic reticulum and the Golgi network is what keeps the structure intact. This explains why Golgi disassembles during mitosis in which this constant influx is interrupted (Misteli, 2001).

As mentioned for the molecular level previously, some conceptual clarifications of self-organization seem to be necessary. Even though it is quite common to describe lower-level components as self-organized (Misteli, 2001, 2009; Sasai 2013), it should be emphasized that it is the nonlinear processes that exemplify self-organization dynamics and not these lower-level components such as organelles. Nonlinear dynamics, which I associate with transitional self-organization, have a role only as an auxiliary element when it comes to the organism. In this context, what is regulatively self-organized is the organism as a whole, and what is transitionally self-organized in lower levels is processual, but not component-based. In most cases, the underlying phenomenon revealed by biological studies appealing to the notion of self-organization is emergence as a process (see Chapter 4). For example, let us consider the association between dynamic instability and self-organization. According to a presumption in this context, "self-organization ensures structural stability without loss of plasticity" (Misteli, 2001, p. 184). The implicit idea here is that the responsiveness of unstable structures enables a dynamic interplay through constant fluctuations and macro changes within the organism (Misteli, 2001). The functional role of the phenomenon is insightfully put forward; yet again, a conceptual questioning is necessary. The main phenomenon in question is dynamic instability, which defines the continuous interactional basis of certain structures such as organelles. This is related to the processual nature of biological structures, as what characterizes the form at a higher level is the constant dynamism at a lower level. However, if the processual basis of dynamic instability is to be considered as a reason for associating the phenomenon with self-organization, there would be a potential for vagueness within the definition. One could argue that the processual basis of stabilized forms in living systems is not limited to dynamic instability, and therefore there is no possibility of demarcating self-organization in terms of dynamic instability. In other words, a liberal attitude toward the usage of the concept of self-organization might create a backlash in the form of scepticism regarding the relevance of self-organization. This is indicative of a lack of philosophical clarification on this issue. Within the research on cellular-level dynamics, it seems possible that the concept of self-organization appeals to researchers most prominently when they are attempting to identify an eccentric situation within the general process-based phenomena (e.g. Urdy, 2012). When dynamic instability is attributed to self-organization, the implicit idea is the bottom-up construction of the biological form on an interactional basis, usually a network of feedbacks based on short-term activations coupled with long-term inhibition (Karsenti, 2008). This kind self-organization is associated with de novo assembly of components, which is alternative to template-based formation. In the former, specific interactions lead to the formation of organelles from scratch, whereas in the latter previous organelles are used as a template to build new organelles. It is found out that de novo structuration is relevant in the formation of centrioles, chromosome-induced spindles, and Golgi (Karsenti, 2008). However, this does not mean that the centriole is self-organized in the sense that it can be formed without the context of the cellular, tissue, and organism-level dynamics. The basis of self-organization is individuation. A component's capacity for individuation at the cellular level is very low and the influence of cellular environment is very high. Regardless of whether the dynamics of organelle formation such as centrioles is spontaneous, nonlinear, or dynamically stabilized, associating these entities with selfhood would lead to an ambiguity concerning the implication of self-organization as an autonomous whole. The organism's regulative self-organization is autonomous, yet a process of organelle formation is not. Thus, aside from the underlying processes, the organelles such as the centriole, in actual context-dependent relations within an organism, should be understood as the sub-elements of regulative self-organization, not as cases of self-organization themselves. Transitional self-organization might be involved in the formation of these organelles, but this processual factor and the organelle as an entity should not be confused with each other.

This brings us to the problem of contextualizing cellular processes within higher levels of biological organization. At the cellular level, cellular shape and morphology of the organelles are highly interdependent, which denotes a loop between the part and the whole as the basis of dynamic instability (Karsenti, 2008). Cells are the chemical factories of the organism, as enzyme activities always occur within cells. Bottom-up realization of cellular activity is formally shaped by the closure of the membrane, whereas top-down implementation has different dimensions in tissue-level functions vis-à-vis organism-level functions. Thus, understanding the dynamics of order at the tissue level would help to reveal how the interlevel causation between the cellular and tissue levels is realized. In this context, below I discuss tissue-level dynamics by addressing the notions of pattern formation and morphogenesis.

Pattern formation is usually co-determined by the interactions due to intracellular activity, cell-to-cell signalling, tissue geometry, and other complex factors such as positional information (see below and Chapter 4 for a discussion of controversies relating to this account). Pattern formation appears in embryogenesis and growth, and it is defined as a synonymous concept of regionalization (Waddington, 1956), which refers to the differentiation of tissue parts (Urdy, 2012, p. 788). This is one of the processes that are typically attributed to self-organization (e.g. Wang, Badea, & Nathans, 2006), and it is not difficult to see the reason behind it. These kinds of processes create the form mainly as a consequence of the internal interactions between the components, which calls into question the preformationist conceptualization that views the ultimate form as the unfolding of an essential element within.

A prominent case of pattern formation is gastrulation, which occurs during the early phase of embryo development. Through this process, the exterior layer is invaginated and the cells move inward along this invaginated layer, forming a multi-layered structure. To explain the dynamics behind embryonic development such as gastrulation, the role of physical factors such as diffusion and gravity as they are constrained into biological processes was studied theoretically (Papaseit, Pochon, & Tabony, 2000). These theoretical studies were then supported by empirical studies proving that direct physical forces play a role in the developmental pathway. For example, the fact that the self-organized development of the embryo is influenced by gravity has been demonstrated in space experiments. In altered gravity conditions (microgravity), it has been revealed that the lack of Earth's gravity leads to pathological conditions or death of the embryo due to the altering of mechanisms such as gene expression (Crawford-Young, 2003). On the other hand, molecular biologists usually focus on precise mechanisms in which genes deterministically control this type of processes (Urdy, 2012). A recent idea that has begun to gain recognition, however, is a synthesis of genetic determination and physical constraints, which I will discuss in the remaining part of this chapter.

Positional information is a concept that can help to overcome this dilemma between gene-centred vs. physicalist understandings, since it is proposed to explain developmental effects by considering both the genetic regulation and the physical condition of the regional differences. All the cells of the embryo have the same genome, yet they differentiate as the embryo transforms into a heterogeneous entity. Differentiation is mainly caused by epigenetic mechanisms, in which certain parts of the genome are activated, whereas other parts are deactivated in each cell. Genes are highly influential in the development of the embryo – which is an influence quite different from the classical essentialist understanding of genes as the coders of certain proteins. Yet, due to positional information, the differentiation of the cells is explained by contextualizing genetic regulation in the spatiotemporal condition of each cell. Thus, the term refers to the context-dependent determination of pattern development where genetic influence is sensitive to the position of cells. During embryo development, each cell reacts to its surrounding by assessing its position within the whole, which is basically a complex feedback response of the cell. Thereby, spatiotemporal non-uniformity acts as a feedback on genetic expression (Urdy, 2012). As a consequence, positional information plays a main role in cell differentiation, and indicates a complex interplay between genetic regulation and local dynamics of order.

Positional information illuminates the question of how cells differentiate and how the heterogeneous form arises even though each of the cells has the same genome. In a way, this heterogeneous response mechanism acts as a formal cause during the early phase of development. In the beginning of the embryo development, the cells are pluripotent, which defines the capacity of the embryonic stem cells to be turned into any type of cells. Pluripotent stem cells basically serve as the potentiality basis of development (see Chapter 4). While the context-dependent feedbacks acts on this potential, cells are shaped into their final form due to the spatial and historical interpretation of their relations. Positional information therefore creates a basis for formal causation acting upon this potential, in which pluripotent cells are the material cause. Thus, it is not the cell as an isolated component of the whole, but the sum of the interrelations between the parts of the whole that overrules the developmental path (see Chapter 4).

This does not solve the emergence of biological form as this problem goes beyond the dynamics of cellular differentiation. This requires going back to the initial question: How does the integration of genetic regulation and physical constraints influence the formation of patterns? The latter element of this integration, that is, mechanical and chemical processes, also relates to the extent to which the physical pattern is a distinguishable phenomenon, and in which ways it is incorporated through the complex genetic regulation. Turing's (1952) classic paper on morphogenesis has proposed an explanation concerning how the chemical processes can lead to heterogeneous form that is similar to the case of embryonic development. According to the basic model, a reaction-diffusion system including at least two chemically interacting components can create the heterogeneous form through a fluctuating process of generation. One of these interactors catalyses both its own and the other component's activity, whereas the other component has an inhibiting influence on the catalyser. An increase in the activity of the catalyser also leads to an increase in the amount of the inhibitor, but this initial catalytic activity is then counterbalanced, since the inhibitor has now accumulated as well. This dynamic interaction between the catalyser and the inhibitor leads to a chaotic fluctuation pattern. The model presumes that inhibitor diffuses faster than the catalyser, which will create a spatially nonuniform pattern where the densities of each component are asymmetrically localized depending on the abovementioned differences between the rates of reaction and diffusion (see Newman & Comper, 1990 for details). In this case, heterogeneity is created due to a process named *diffusion-driven instability*.

Reaction-diffusion models are used to understand the creation of striped patterns that are thought to be efficient in the generation of limbs during embryo development (Newman & Linde-Medina, 2013, p. 278) and other phenomena such as mammalian coat markings, butterfly wing patterns, pigmentation in species such as molluscs and zebrafish, etc. (Urdy, 2012). The studies in this area since Turing have shown that reaction-diffusion mechanisms can never produce biological form on their own. Instead, the basic mechanism is efficient when it is combined with gene expression, e.g., findings have shown that this dynamic can provide the variation within the rates of protein synthesis (Urdy, 2012). Since the protein synthesis is a consequence of gene expression, this shows that morphogenetic pattern is complementary to the factors of genetic determination.

Patterns appear through the bottom-up organization of the cells, and just like the molecular level, stochastic elements are usually effective in the formation of tissue patterns at macro scale. For example, in one of the studies based on the human mammary epithelial cells (Chanson et al., 2011), researchers established the bilayer formation (luminal and myoepithelial layers) of the mammary tissue in laboratory conditions. Here, tissue morphogenesis was driven by the heterogeneous expression of E-cadherin, which is a protein that enables adhesion among cells. Another study has found that global signalling, which is a regulative element at the individual level, roughly determines hair patterning in mice (Wang et al., 2006). According to this study, the local interaction rule of alignment, which presumes that hair follicles force neighbouring ones to align with themselves, determines the final shape. The authors state that this is a stochastic process that is similar to the alignment of the ferromagnet, since both the electron spins in a ferromagnet and the different angles of follicle alignment through the formation of the hair pattern spread on a basis of random differentiation (Wang et al., 2006). This kind of self-ordering process has strong evidential support from various sources, demonstrating that stochasticity can play a major role in the emergence of ordered structure through local interactions. These studies have revealed that stochasticity at the micro level permeates into the macro, indicating an interlevel connection.

Processes such as morphogenesis and pattern formation concern the diachronic basis of emerging order, which means that emergence is not only due to the static integration of parts, but it is a specific type of temporality that creates the form. In that regard, the mentioned processes exemplify transitions due to nonlinear factors, which I categorically defined under transitional self-organization. Yet, the dynamics of order can be influential both in transitional and relatively static ways. Tissue immiscibility is an example of the latter. Immiscibility denotes the fact that “tissues from different sources often behave as distinct fluid phases” and “the mixtures of cells from different tissues will sort out into homotypic islands and lakes, and will eventually separate out completely, like a suspension of oil in water" (Newman & Comper, 1990, p. 3). The interactions that lead to immiscibility can be either in the form of attachment between the same type of cells or excluding the cells of different types. The extracellular matrix can also contribute to tissue immiscibility by causing the tissue to act as a viscoelastic sheet (Newman et al., 2003).

Phenomena such as immiscibility depend on the physical properties of tissues. Take the role of diffusion as a physical factor of organization. During pattern formation, signal molecules diffuse by creating feed-forward mechanisms, which contribute to the emergence of pattern (Newman & Comper, 1990). This implies that diffusion as a direct physical factor is constrained through biological organization. In this regard, Newman et al. (2003) classify these biophysical factors as generic properties,[41] including the aforementioned processes of reaction-diffusing coupling and tissue immiscibility along with others such as differential adhesion, biochemical oscillation, multi-stability, and mechano-chemical excitability. According to this approach, these processes are under the influence of generic factors in the sense that mechanical or chemical factors directly determine their nature, which makes them different from genetic factors that are the products of long-term evolution. In the following section, I will explain this distinction in more detail as a part of the problem of biological regulation.

Thus far, I have explained how the physical dynamics of emergent order such as the self-assembly of a phospholipid bilayer and patterns formed at the tissue level constitute complementary elements of the organism's organization. I have also explained how these lower-level dynamics are encapsulated in regulative self-organization, and realized due to the autonomy of an individual, which is why they cannot be considered to be self-organized per se. In this perspective, levels of

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[41] However, this notion is later revised as biogeneric properties due to the following reason: "The mechanisms that generate the multilayered initial stages (gastrulae) of animal embryos, pancreatic islets, and tetrapod limb buds, are therefore not entirely «generic» in that they are not precisely the ones driving similar-appearing outcomes in nonliving systems. They nonetheless can be considered 'biogeneric' in the sense of employing generic physical mechanisms to organize biological materials (e.g., aggregates of cells) in novel ways" (Moss & Newman, 2016, p. 104).

organization constitute the layered solidification of emergent dynamics as a consequence of the organism’s evolution. Thus, the emergent order permeates through the levels of organization. This brings us to the main issue of the following part of this chapter, as the multicellular organism constitutes the milieu of the subsystemic relations. In other words, regulative self-organization in the Kantian sense encapsulates the dynamics of spontaneous order at lower levels. The appearance and the exploiting of these kinds of capacities indicate that the organism’s function is far from being a one-dimensional closure.

2. Regulative Control at the Organism Level

In the following sections, I will discuss how different aspects of emergent dynamics contribute to the development of unified wholes. This requires clarifying two issues. The first issue is how emergent dynamics inherent in organic matter are stabilized further due to genetic regulation. This also relates to an evolutionary transformation from primitive dynamics of self-organization to biological regulation (Newman et al., 2003). The second issue is how centralized mechanisms such as genetic regulatory networks, hormonal signals, and immune systems enable the consistency of regulative self-organization at the organism level. In addition to these two points, it must also be emphasized that local dynamics of order at lower levels are unified in the notion of functional integrity. Regulative self-organization of an organism leads to an individuated constraint in the form of multiple functionalities by exploiting the capacity of the spontaneous dynamics at lower levels. Moreover, this type of multiple-levels approach is critical towards the view that genetic mechanisms are the ultimate causal agent of biological organization. This is because intralevel relations at the molecular, cellular, and tissue level are highly influenced by the biophysical nature of the biological order. This approach also helps to reveal how centralized networks such as the immune system act upon the local dynamics of spontaneous order.

Organisms are processes (Bateson et al., 2001; Dupré, 2012), and more specifically, they are regulatory processes. Based on this perspective, it is the processual nature of functions that integrates lower-level dynamics in specific goal-directed processes. The organism’s functions are triggered by responses to internal and external stimuli through the activity of complex network of feedback responses to maintain homeostatic conditions.[42] The functions of the organism are self-organized, which also requires rejecting the mechanical determinism in favour of diachronic emergence. These self-organized functions of the organism are realized in the possibility space that is enabled by the synchronicity of causal relations (see Chapter 4). In the rest of this chapter, I explain how the processual nature of functions can be supported from the perspective of levels of organization. The processual nature of function serves as the basis for top-down causation acting upon the organism, which determines how organizational potentials at lower levels are actualized. Depending on the context of the function, centralized mechanisms utilize the rest of the organism as a potential, which can be considered as interlevel causation realized as the interventions into the lower-level dynamics.

2.1 Genetic regulation as the constraint of the organism

In this section, I consider the role of genes in the regulative self-organization of the organism. As an alternative to genetic reductionism, Stuart Newman's theoretical perspective regards genes as to the stabilization and the regulatory unification of the organism, co-existing with the dynamics of pattern formation due to generic properties of the organic matter (Newman et al., 2003). For now, I approach this issue in relation to levels of organization, yet I will go back to the discussion on the role of genes in the light of Newman's ideas later.

In several studies discussing self-organization as a basis of the morphological properties, the physical constraint is mentioned due to its role in biological organization (Bonner, 1996; Leijnen, Heskes, & Deacon, 2016). Newman and Comper (1990) reverse this approach by claiming that the constraint is in fact the biological regulation. It is the genetic regulation, by creating organizational robustness, that acts upon the roughly shaped form due to morphogenetic dynamics. They explain the difference between physical and organizational dynamics of the biological form by distinguishing between genetic and generic

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[42] Nevertheless, I also emphasized why this homeostatic condition should not be considered as a mechanistically precise control of processes, which distinguished this position from autopoiesis.

properties. According to this distinction, generic properties refer to the direct influence of physical factors, such as the reaction-diffusion coupling (see Section 1.3). On the other hand, genetic properties refer to the regulatory function of the genes acting through genetic circuits and cell-to-cell communications, which denote a more precise control at the molecular level. These two types of properties are integrated, since the "generic mechanisms are complementary to and interdependent with genetic mechanisms" (Newman & Comper, 1990, p. 1). By definition, generic properties refer to the properties that are common to all organisms.

The difference between generic and genetic properties is also reflected in the evolutionary presumptions with a hypothesis on the origin of life (Newman et al., 2003). According to this, Darwinian evolution by genetic inheritance was preceded by a pre-Darwinian phase of evolution in which morphogens and other direct physico-chemical factors were more efficient. Genetic programming appeared in the last half billion years of evolution and brought organizational robustness through precise regulatory mechanisms. Prior to the strict genetic inheritance, the adaptations of organisms were based on physico-chemical parameters that were more closely attached to their surroundings (Newman et al., 2003). The first metazoan organisms were polygenetic morphotypes in the form of self-organized cells acting as viscoelastic sheets. Thus, evolution has proceeded from the morphotype to the genotype, and monogenetic organisms are actually the products of a later phase (Newman et al., 2003).

The abovementioned approach portrays the organism with multiple dimensions of causal processes, and proposes an alternative solution to the question of the stabilization of form by unifying evolutionary and physiological perspectives. Causation can appear as reaction-diffusion processes, genetic regulations, or direct physical forces such as gravity. This approach to self-organization attempts to address the complex coalescence of these causes with different dimensions by asking questions such as how the inert cells "spontaneously organize into countercurrent microfinger patterns under the influence of gravity" (Newman & Comper, 1990, p. 9). Self-organization, in this sense, provides a theoretical basis to unify these dimensions. From this perspective, even though it is not always easy to distinguish the roles of spontaneity, physical force, and genetic regulation from each other, the role of physical forces such as gravity is now better understood (Crawford-Young, 2003).

The distinction between generic and genetic factors also supports the philosophical analysis of interlevel causation within the organism. Generic factors can be considered within the scope of bottom-up construction of order, as they depend on the utilization of direct mechanical forces. The utilization of mechanical forces is a widespread phenomenon, since these forces contribute to several organizational processes from creating localized order in tissues to the pattern formation and gene expression. For example, growing empirical evidence shows that through genetic expression, mechanical forces are canalized into the biochemical machinery of cells. Different dimensions of organization diversifying within a spectrum from mechanical forces to complex regulatory networks require an approach that includes interlevel causation. This kind of interlevel approach has been recently applied to understand cancer development (Urdy, 2012). In the growth of a tumour, a typical case of malfunction is studied at the cellular level, since the tumorous cells diverge from their cyclic development of controlled division, and proliferate in great amounts. On the other hand, an alternative theory based on the concept of tissue self-organization challenges the standard view of somatic mutation theory by questioning the role of cellular mutation as the only causal agent of cancer. According to this, some researchers claim that cancer is not a disease caused solely by mutations. In fact, patterns at the tissue level are also involved, and the tumour is also a result of a malfunction in the interactions between cells. This has been demonstrated by the experiments in which a healthy tissue structure does not allow the spreading of the cancer cells (e.g., Soto & Sonnenschein, 2004; Rubin, 2006). This supports the need to address the issue from a perspective including regulative self-organization: Cancer at the tissue-level organization is to be investigated due to the emergence of sub-systemic elements within the self-organized whole.

I previously explained how physical forces and morphogenetic dynamics such as reaction-diffusion coupling are integrated with gene expression. The regulative organization of the organism is realized through the epigenetic mechanisms in which gene activity is highly influenced by the organizational context. In the past, genes have only been regarded as the coders of specific proteins, but the current view is shifting toward a broader understanding that considers both the interaction of genes with the cytoplasm and the environmental effects on the epigenetic differentiation of the gene expression (Moss, 2003; Griffiths & Stotz, 2006). As will be addressed in detail in the next chapter, only a small percentage of genes that are known as exons are used in coding proteins, whereas introns, which are the gene sequences that are not used in coding, usually have regulative functions. These parts were previously named as junk DNA, as they have been thought to be useless. Now, revealing the regulatory function of genes is revolutionizing our understanding on the issue. The reciprocity between genetic activity and other metabolic activities is better acknowledged with recent studies on epigenetics, thus vindicating the self-organization view concerning the organism. In terms of levels of organization, the regulatory networks of genes do not necessarily correspond to a specific dimension of order, but a biological way of constraining this order. This is because genetic activity serves as a kind of distributed interface within the organism. Through this regulative activity, interlevel causation by the centralized functions and intralevel causation at lower levels are unified. Therefore, genetic regulation should be understood as a holistic integration of the organization at every level. In summary, Newman’s approach asserts that genes act upon physico-chemical dynamics of order that are associated with a pre-Darwinian phase of evolution. I have argued that this is a viewpoint that helps to reconsider genetics due to an organism-level explanation, which will now be continued by examining other aspects of centralized regulation.

2.2 Centralized mechanisms of organization

The main question that I dealt with in Sections 1.1 and 1.2 was primarily how the bottom-up dynamics of order perform laterally. I argued both thermodynamic and kinetic factors are central for molecular-level functionality. Moreover, morphotypical elements such as pattern formation supervene on molecular stability. Then, in Section 2.1, I explained how generic and genetic properties co-determine the holistic nature of the organization. In this section, I consider the centralized elements of organization that engage in vertical implementation of organization. What characterizes the organism's regulative self-organization is the interplay between bottom-up and top-down dynamics, which is caused by the asymmetrical character of the regulatory control. As a consequence, not all the parts within the organism have the same controlling capacities (Bich, Mossio, Ruiz-Mirazo, & Moreno, 2016). Systemic functions of the organism, such as the function of the immune system, or the functionality that enables the energy circulation within the body, are processual downward causes in the organism. This is because all the parts behave, trigger, and respond to one another in order to maintain their functionality. Therefore, the organism as a process is in fact a complex and constant activity of responsiveness against any perturbation. This functionality is the downward cause that determines the activity of each part within the organism.

Before explaining what is meant by functions as downward causes, the processual nature of functions should be clarified. In process view, spatiotemporality characterizes the materiality. Yet, for the sake of analysis, either the spatiality or temporality can be treated as alternative foci when the organism is studied as a regulatory process. For example, as the mechanisms such as the circadian rhythm characterizes regulation as a process of oscillation, these kind of mechanisms can be analysed in a way that temporality is primary, whereas in other mechanisms such as genetic regulatory networks, switched on and switched off states of genes can be analysed by prioritizing spatiality of the gene activity. However, even though circadian rhythm and genetic circuits can be isolated as the subjects of scientific research, a philosophical understanding of the organism as a process has to consider the fact that analytical reduction of these mechanisms either to temporality or spatiality is an empirical operation. Thus, this empirical operation should not lead us to move away from the ontological fact that organisms are processes.

The autonomous perspective is helpful as a theoretical framework to explain the organism's individuality by pointing out the integration between centralized mechanisms of function and distributed networks of regulation (Moreno & Mossio, 2015). This approach emphasizes that the centralized mechanisms of biological functions depend on the asymmetry between the controlling and the controlled (Mossio, Bich, & Moreno, 2013; Bich et al., 2016, p. 236), which I regard as an essential factor. For example, in the chemotactic movement of the bacteria, the receptor complex and the signal transduction pathway create the controlling action, whereas the movement of flagella is controlled by this element (Bich et al., 2016, p. 243). This asymmetric consideration can be applied to the functioning of a multicellular organism through levels of organization. In this way, lower-level phenomena would be incorporated within the organization.[43] In biological systems, aggregation of parts creates emergent properties that have been discussed in the context of various examples in this chapter. On several counts, I identified cases where the emergence of order is from the bottom, appearing through local interactions, or physical properties such as the immiscibility of tissues, which are compositionally integrated, but causally non-identical with the regulatory networks. As regulative organization is a product of the interplay between these bottom-up dynamics and centralized functions, through the centralized elements, downward control is exerted on the organism. Functional circuits constitute the spatial axis of this top-down control, whereas the temporal axis is causal loops, actualizing as the metabolic oscillations, leading to short-term or long-term periodic changes. Why downward causation, instead of the holistic control? At first glance, downward causation seems problematic. Since the self-organized organism is individuated, and the networks are distributed, one could argue that the control is holistic, but not implemented by the top-down mechanisms.

However, as I argued before, organizational hierarchy and self-organization do not exclude each other. At this point, the concept of *decoupling,* which was first

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[43] The autonomous perspective emphasizes the role of micro-regulatory processes such as the lac operon mechanism, which enables the regulatory system to shift between the modes of digestion in order to increase the energy efficiency (Bich et al., 2016). Nevertheless, as discussed in the previous chapter, this approach underestimates the role of emergent order, which in turn paves the way to an implicit overemphasis on the regulatory functions. I propose that the role of spontaneous dynamics is more prominent, which calls into question the omnipotent efficiency of micro-regulation. If the bottom-up emergence of the biological materiality is ignored, one could miscategorise the actual dynamics of order by appealing to the cybernetic account of controlling the body. Despite appreciating the explanatory value of the autonomous perspective on the hierarchical nature of organization in a multicellular organism, these points identify a limitation within this approach inherited from the mechanistic tradition. In fact, as mentioned before, autonomous perspective is also critical to these preceding theories in many ways, but I believe that the critical stance towards the cybernetic notion of organization should be taken a step further.

proposed in the theory of cybernetics, and then applied within autopoiesis and the autonomous perspective, helps to reveal the downward nature of the regulatory systems. Decoupling refers to the situation where some elements of organization become independent from the materiality of the causal cycle that it influences, and explains the abovementioned asymmetry between controlling and the controlled. The specialized control is based on this type of asymmetry, as the regulatory network is dynamically decoupled from the functional cycle (Bich et al., 2016). This is because the disruption of the functional cycle does not immediately influence the controlling system. For example, the hormonal signalling, as a centralized mechanism of communication within the organism, is decoupled from the cellular processes it affects. A few molecules are sufficient to initiate signalling cascades, which is why a small energy investment can sustain the function. In fact, hormone production is still dependent on the chemical activities within the cells that are regulated by hormones, since a disruption of the cellular activity would eventually cause a disruption with hormone production as well. But this relationship of dependence is weak, since in the short term, the healthy functioning of hormones is decoupled from the materiality of the cellular activity. This asymmetry creates a potential for the controlling network to be partially independent from the rest of the body. This potential, which is due to being decoupled from the internal, is used to regulate the organism depending on external stimuli. Since a small amount of hormones is sufficient to create the effect, hormones are highly influential in regulative system, but not influenced by the parts to the same extent. Therefore, hormones can act in accordance with the holistic needs of the organism, mostly determined by the interaction between the internal and the external. Decoupling also enables centralization. This is due to the centralized functions of the organism, maybe not necessarily to be found at a specific location within, but in the systemic behaviour of the centralized, goal-directed processes.

The role of the brain and the nervous system in centralization of the organization is evident, but actually a less salient but more remarkable example is the immune system. Below, I discuss the immune system in the context of the notion of self-organization. There are three reasons for focusing on this example. First, the immune system is a remarkable case that demonstrates how a function is implemented as a top-down cause, and how the individuality is highly dependent upon this top-down activity. In the case of immune system, the goal of the function is to neutralize possible threats to the body, and the system performs this function by self-regulating its activity and improving its capacity by recording the molecular traces of previous interactions. Second, the way that the immune system functions shows that in self-organization, as well as the semi-autonomous parts of the system each performing its task, a correlated activity, corresponding to an emergent individuation of the system is essential. Third, the immune system offers support to a broader point that is emphasized throughout this chapter, that is, the processes of the organism that bases the emergent dynamics of order are not mechanistically precise, but essentially stochastic.

As a reflection of the asymmetry between organizational hierarchy and compositional hierarchy, centralized structures such as the immune system are not materially composite parts of the body, but they are functionally integrated through specific goal-directed activities. For the immune system, the goal-directed activity is to detect and regulate potentially harmful pathogens. The centralized function depends on distinguishing between the self and the non-self through this activity. Failure of this function, as in the autoimmune diseases, occurs when the immune system misidentifies healthy tissues as a potential threat. In order to solve the questions due to selfhood, since Frank Macfarlane Burnet, who was involved in early clinical research on autoimmune diseases, researchers have often been interested in the philosophical problems with individuality, cybernetics, and information theory (Anderson & Mackay, 2014).

The body's immune system creates various types of leukocytes in order to cope with invaders consisting of several antigens. An essential challenge for destroying invaders is the body's capacity to distinguish these unwanted cells from its own cells and symbiotic microbiota. The immune cells recognize possible pathogens with an attachment similar to a key-lock mechanism. However, the system cannot produce all the keys (antigen receptors) for any possible lock (new antigens) by random differentiation due to the huge number of possible combinations of the binding sites. As I explain below, a guided diversification is the main strategy to solve this problem by allowing a certain degree of randomness in the production of immune cells. The way that the immune system works proves that, instead of precise mechanistic control at the molecular level, functional integrity depends on a goal-directed incorporation of lower-level dynamics producing organizational variations.

Atlan and Cohen (2006) remark that the immune system is self-organized, as its activity is constantly modified due to the history of interactions with new antigens. The immune self is a reference point in the antigen induction. The information that is necessary to identify pathogens is produced through the interactions: the immune system acquires a distributed memory of the previous antigens, T-cells differentiate into more specialized cells according to counteracts, and "the receptor repertoire for antigens is somatically generated by random genetic recombinations and mutations of the receptor genes" (Atlan & Cohen, 2006, p. 133). To explain the principles of the immune system, Atlan and Cohen (2006) propose that immune interactions can be understood as metaphorical form of language, which refers to *meaning*. In the same way that people require some shared history to be able to convey meaning, i.e., the same language, similar reference points, contexts, and associations, the meaning in the self-organized immune activity is dependent on the historical context of the germ-line that includes the evolutionary catalogue of the antigens, and the history of the individual host, as the meaning is provided by the combined application of the germ line instruction and the individual experience (Atlan & Cohen, 2006).

Just as the meaning of a sentence is conveyed due to its semantic context in a text, the implications of signals within the immune system reflect the evolutionary background and the individual's life history. The interactions between pathogens and immune cells are transformed through these processes. Immune cells can differentiate pathogens from body's own cells. Detecting and annihilating pathogens is the main goal of the function acting as a downward cause, which orchestrates the molecular memory of the system, complex networks of signalling, and genetic transcriptions that are practiced in accordance with this background. For example, the antigen producing cell and a T-cell communicate with each other. According to the analogy, antigen's epitope (the main element of binding) functions as a subject because it is the agent that can differentiate to perform its function through its interaction with the pathogen. On the other hand, the ancillary signal functions as a predicate of a meaningful sentence, since it determines the instructions given to the subject, the epitome, depending on the specific context of the situation.

Similar to the case of protein folding, antigen production is made through exploring a possibility space by constantly using the feedback from actual interactions, which occurs by effectively using the internal randomness of the system. There are approximately 10^{10} and 10^{20} possible antigen combinations, and therefore it is impossible to recognize all possible occurrences of antigens in a pre-determined way (Atlan & Cohen, 2006, p. 127). Alternatively, “the diversity of the antigen receptors is fashioned by processes of genetic recombination, mutation, and random insertion of nucleotides in the genes that encode the receptors” (Atlan & Cohen, 2006, p. 125). New immune cells are “trained” by keeping the record from the feedback from interactions with the body’s own cells. Thus, top-down exercise of this regulative self-organization is far from exhibiting an omnipresent control of a machine-like system. As a result, contrary to noise-reduction approach to information (Shannon & Weaver, 1964), it is pointed out that redundancy enables synonymous correlations, making the message more robust against noise. In this context, a certain degree of noise is shown to be useful to discover novel ways of reorganization (Atlan & Cohen, 1998, 2006).

Atlan’s (1974, 2000) general theoretical approach indicates not only the importance of the top-down implementation of the centralized mechanisms, but also the role of contingency in regulative activities that have been previously discussed in this chapter. Moreover, his perspective calls into question a certain way of understanding information considered as a certain catalogue of codes, and with it, the notion of the gene as the ultimate bearer of information deterministically coding the elements of organization. Instead, information is produced through the history of self-organized regulation in an unpredictable environment by exploiting the capacity of stochasticity. In the abovementioned example, the meaning depends on the stochastic application of the molecular traces from the previous interactions. So, obviously, the meaning is not created in a cognitive mechanism, but through the alteration of binding sites of the immune cells depending on a constant internal communication within the body that interprets the evolutionary background of the interactions. The analogy suggested in this example is also consistent with theoretical claims on hierarchical organization by Pattee (1972), whose ideas on constraint have been briefly discussed in the preceding chapter. Pattee (1972) states that structural constraints are different from hierarchical constraints. The former depend on the elimination of the degrees of freedom, whereas the latter "select from a set of possible states because of relatively fixed but conditional correlations between the particles of the collection" (Pattee, 1972, p. 5). He goes on to argue that hierarchical control requires a structure similar to language because only these types of systems enable the operations that are still based on, but are relatively independent from the physical structure due to symbolic nature of interrelations. This also creates an evolutionary potential by forming certain rules, which act as a criteria for further change, similar to a grammatical structure (Pattee, 1972, p. 10).

I explain the notions of contingency and potentiality in relation to biological functions in more detail in the next chapter. The abovementioned example serves as an empirical introduction to this idea. The way the immune system works indicates that a specific function of the organism is a goal-directed process, and it is a top-down cause, because in the context of the immune system, the goal, which is the neutralization of potential pathogens, is primary. Thus, other centralized functions and lower-level dynamics are utilized as the auxiliary elements of this functionality. This is not to say that the top-down causation of this specific function is absolute, since in other contexts of functionality, there could be compromises from the main goal of the immune system. For example, during the pregnancy, the development of the embryo within the mammalian organism requires this kind of compromise, since the existence of the embryo requires a suppression of the immune reaction towards the embryo. Self-regulating functions also show that the organism's organization is not fully predetermined, either in the sense of genetic predetermination, or in the sense of mechanical determinism. The former is due to the fact that the system is constructed by acquiring new information during ontogeny, which is in line with Oyama's (2000) main proposal concerning the ontogeny of information. The latter is due to the fact that new capabilities of performing the function is explored in a possibility area in which the system improves itself by responding to its own activity.

Conclusion

In this chapter, I considered both the empirical cases and theoretical assumptions concerning the emergence of order within the organism. I explained why both the bottom-up and top-down dynamics are essential for considering the organism as an individuated whole, and criticized some of the issues arising from overemphasizing the role of regulative control. Dynamics of order at multiple levels of organization suggest that contingency is an essential element of biological organization. On the other hand, the regulative self-organization of the organism is dependent on multiply realizable pathways, asymmetric control, and centralized activities. As a main point, I showed why self-organization is not characterized by an integration of equally efficient parts, and why a causal hierarchy depending on the context of goal-directed functions acting as downward causes is consistent with the organism's self-organization. In this type of self-organization, the parts are interdependent, but the interdependency is inherently causally asymmetric, which means that all the parts are not equally dependent on each other, but their dependency is subject to the manipulation of functions as a consequence of the relation between the organism and its environment. In this organization, parts are imperfectly integrated; since they communicate with each other through fulfilling the requirements of the homeostatic control.

Moreover, the way that parts communicate with one another calls into question the applicability of precise mechanisms coding the structure of the organism, in so far as this understanding does not consider the novel elements of information that are produced through the history of interactions. In order to reconceptualise the internal communication in the context of immunology, the language metaphor is proposed (Atlan & Cohen, 2006). According to this, it is claimed that involvement within centralized networks gives the parts the "meaning" of their task. I indicated some further implications can be derived based on this perspective, such as how meaning could also be relevant for a better understanding of subsystemic agency. It is beyond the remit of this thesis to develop a more detailed analysis of the notion of information and meaning. Still, in the last chapter, I will discuss other related aspects to this question such as contingency. In this sense, the studies on self-organization discussed in this chapter help to dissociate self-organization from its cybernetic heritage, which mainly focused on the elimination of contingency and understood the organism as a machine (Keller, 2009; Nicholson, 2014).

Now, in the light of the analysis based on genetic and generic properties, let us return to the problem that was defined in Section 1.2, which concerns the physical basis of the biological form. The properties of the organisms that Thompson and other structuralists have tried to illuminate are referred to as internal properties, or physical forces (Bonner, 1996). This traditional approach is maintained today in some sense, but a philosophical problem is immediately striking. Aren't all the properties internal and all the forces physical within organisms? Environmental influences such as selective pressures are external, but the organism's properties are always internal. Gravity, diffusion, or forces such as cohesive attraction that enables the water to move up within a trunk of a tree are directly physical forces, but so are complex organizational networks.

At this point, the categorical understanding of causal processes as either generic or genetic factors are relevant for the physicalist understanding of the biological organization. Physical forces are incorporated in extraordinary ways within organisms, as the organizational context manipulates these forces from which a unique area of study emerges that is irreducible to the mechanical understanding of these forces in isolation. This emergent context is a history-dependent case, as is well known, due to evolution. Direct physical forces such as gravity are still analysed as distinguishable forces, but this kind of direct role is generally limited to acting as either an inducer or contributor to the internal organization, which is intrinsically self-organized. Due to this new causal capacity, a vectorial analysis of forces has little to do with this new kind of causation. In that sense, Kant's prediction that there cannot be a Newton of the grassblade is still relevant. New research areas such as quantum mechanics, physics of nonlinear systems, or the methodology of the statistical mechanics have been adapted to biology to fill this deficiency. Nevertheless, this does not change the fact that the causation of the organism has an emergent basis, and empirically, this kind of application of physics is complementary at best.

It is the relational context that underlies the emergent causal capacity of biology as a modified causation of physical forces. In this chapter, I dealt with the role of emergent dynamics within the organism. However, just like self-organization, emergence is a concept that is subject to philosophical conflicts. In that regard, I have not gone into the philosophical problem of emergence directly. As will be shown in the next chapter, the problem of diachronic emergence is yet to be solved, and the organism’s self-organization can cast new light on this problem.

Chapter Four

Emergence, Temporality of Form, and Potentiality

Introduction

The previous chapters have addressed the historical development of research on emergent order and examined various examples concerning the dynamics of pattern formation both in non-living and living systems. It was emphasized that transitional dynamics of self-organization are restricted to processes of non-equilibrium conditions; yet they are also incorporated within the organism's regulation. Since the dynamism of a spontaneous transformation is exhausted by reaching an end-state, processes of crystallization, convection cells, or chemical oscillations cannot have constant organization. Only living systems are characterized by dynamic form that incorporates organizational stability and perpetuated potential for change. The dynamic form of the organism also indicates that the organism is an open process, which is why explaining its organization simply due to stabilization and robustness would be insufficient. A perfect stability does not characterize the form of the organism. Rather, the organism's relative stability depends on internalizing external contingency. In this sense, the investigation of the organism's organization should explain how both the constant dynamism and the individuation throughout the lifespan of the organism are reconciled.

The reconciliation of individuality and constant potential for change requires an understanding of the emergent nature of the organism's organization. Philosophical investigation of emergence in relation to part-whole dynamics is useful in this sense. A basic approach involves considering emergent properties as caused by a rearrangement of parts. This suggests that the contribution of the parts to the whole is sensitive to the context of interrelations, and a new arrangement of parts might require a redefinition of the causal role of the parts within the system (Wimsatt, 1997). Although this kind of emphasis on context-sensitivity is essential, which should be understood in the context of nonlinearity, the philosophical implications of emergence are far greater. When it comes to living systems, emergence cannot be reduced to a distinction between decomposable parts and their interrelations, as this would lead to ignoring the radical implications of relationality and potentiality within these systems. Thus, I claim that a thorough understanding of emergence lies in the profound nature of relationality. This is beyond merely stating that a part's relational context is what defines its parthood, and implies that a whole is nothing but its relations. Furthermore, emergence takes place due the potential for these relations to create the dynamic form. This transforms the system both by using the system's own resources and by rearranging its association with external conditions. The potentiality of the organism, which refers to the idea that alternative network relations within the system can perform equivalent functions, is key to the organism's organization. This is an essential aspect that connects the ideas of self-organization with emergence. In an organic whole, reciprocal relations that are internal to the system have a primary role, as the parts are sensitive to each other, and feedback loops determine the regulation of the whole. Thus, living systems can shift between alternative organizational states.

Potentiality is a precondition of regulative self-organization, but to explain the latter, it is also necessary to first consider the philosophical problems with emergence. A crucial issue is the temporal dimension of organization. The underlying dynamics of regulative self-organization are to be found in diachronic emergence. On the other hand, it is claimed that emergent properties in the whole exist synchronically with the parts, and therefore the emergence of the whole is not a matter of causal relations (Kim, 1999; Hulswit, 2005). As a solution to this problem, I claim that a synchronous condition embodies diachronicity within it, and what we perceive as synchronous is a de facto situation of formal stability. This suggests that the organism's change over time, which is diachronic, is not reducible to certain sequential states, as there is a limit to the heterogeneous potential of the internal relations. Moreover, I disagree with the abovementioned claim by Kim that the existence of the parts and the whole refers only to a synchronic relation, but not a diachronic causation. The synchronous condition is nothing but the individuation dynamics, which is the basis of the emergent nature of the regulative self-organization. The final element of my argument concerns biological oscillations. In the first chapter, I distinguished transitional and regulative dynamics of self-organization, and then, throughout this work, I have attempted to demonstrate how transitional dynamics due to nonlinear causality are encapsulated in the self-regulation of the organism. Biological oscillations appear as a case where these nonlinear factors are realized. From the development of the embryo to heartbeats and the circadian clock, I consider how these oscillations as the rhythm of life determine biological form through which perpetuated potential for change and individuation dynamics are reconciled.

In Section 1, I discuss the philosophical problems with emergence to introduce the challenges against the notion of regulative self-organization. One of the interpretations of emergence is due to constraints, and in this respect, this section is also a continuation of the discussion on constraints that I began in the previous chapter. In Section 2, I examine the processual basis of the organism's form, as this serves as a basis for introducing other ideas in the following section such as potentiality and temporality. I address the notion of formal cause, which is often mentioned in contemporary discussions on the organism. Following this, I consider the same problem in terms of relationality and contingency from an evolutionary perspective. I close this section by discussing alternative accounts of the organism's form in contemporary philosophy of biology. I critically examine developmental systems theory (DST), gene-centric explanation, and structuralism. Gene-centric explanation reduces formal cause to genes. Structuralism includes certain potential drawbacks due to ignoring the material context of the biological relationality. Although DST is distinguished among these approaches due to emphasizing the self-organized nature of the organism and promoting epigenesis (see Section 3.3), it is criticized for overemphasizing the role of contingency and for ignoring the physico-chemical basis of self-organization (Weber & Depew, 2001). Finally in Section 3, I focus on the questions that I raised in the preceding sections concerning emergence and form. First, this consists of a critique of the mechanistic approach, since Newtonian mechanicism does not allow for the identification of the dynamics that are specific to biological systems. Second, I explain why the potentiality of biological organization cannot be understood through efficient causes. Last, I return to the question of emergence: I explain the abovementioned argument concerning diachronic emergence as a realization of nonlinear dynamics. In this context, I discuss the role of biological oscillators.

1. Ways of Emerging

In discussions of self-organization, it is often emphasized that biological systems have emergent properties due to nonlinear interactions (Weber & Depew, 1996; Thelen, 2002; Witherington, 2014), which is a point that is also central to the main arguments of this work. However, without engaging with the underlying philosophical problems, the acknowledgment of the role of nonlinearity would only be descriptive at best. Therefore, in this section I will offer clarification of the concept of emergence; i.e. how it is defined and what kind of philosophical questions are related to it. In my analysis, I will show that there are different understandings of the concept of emergence, and also different stances within each way of understanding. In general, there are three different contexts concerning the emergent nature of biological processes, namely: emergence due to biological organization vis-à-vis the physical qualities, emergence due to macro level as a result of micro level, and finally, emergence due to constitution of a whole as a result of the parts that make the whole. In the first context, the universality of the laws of nature and its application to biological processes is a central problem. An explanation of this issue relates to the history-dependence of the evolving systems (Mitchell, 2012). In the second context, the main issue is whether the qualitative nature of the macro-level phenomena can be reduced to the quantitative at the micro level. The third context, which concerns emergence in part-whole relations, is the most controversial of the three as it is associated with some currently unsolved dynamics concerning the physicality of the systems. It is the processual nature of part-whole relations that paves the way for a new understanding of the organism’s self-organization. By analysing the concept of emergence in these three contexts, I will show how universal dynamics of emergence are instantiated in the ontogeny of the organism, which also demonstrates the relevance of the issue for regulative self-organization. This is preliminary to a discussion on the relationality of biological systems in the next section.

In opposition to the account that calls into question the ontological basis of emergence based on the synchronic nature of emergent properties (Kim, 1999), I agree with the position that emergence is a matter of temporality (Mitchell, 2012). In other words, emergence is a diachronic phenomenon. My account of diachronic emergence implies that emergence is ontological, which is sometimes referred to as strong emergence as opposed to weak emergence (Bedau, 1997, 2002; Wilson, 2013). Moreover, my position suggests that emergence should be understood by looking into the system's transformation, but not the whole's capacity at a certain moment. Without time, emergent properties can be reduced to a certain micro-structural state, yet this would not allow us to understand the diachronic aspect of the problem. The argument that the whole cannot be reduced to a static composition of parts also relates to the self-organization of the organism, as the emergent nature of the organism is due to the dynamism of internal relations.

I begin by considering the question of emergent complexity, which is also related to the constraint interpretation of emergence. The emergence of new constraints is a feature of evolving systems, and not directly related to the question of emergence in ontogeny. Still, constraint interpretation of emergence addresses the main problems of this work by focusing on the relational nature of biological systems, which will be discussed in more detail in the second part of this chapter. This problem relates to an old discussion of whether biological systems are reducible to their physical properties or not. Until the nineteenth century, the argument for emergence in this context was based on vitalism against mechanism, claiming that there has to be more than materiality – an element which is referred to as *entelekhia*, or sometimes, soul – for life to appear.[44] Vitalism has lost support over time due to scientific progress that has led to a better understanding of the

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[44] On the other hand, it is emphasized that vitalism, which was represented by researchers such as Driesch, was nothing more than the recognition of the organism as an object of study that is fundamentally different from other objects (Goodwin, 1982). Also, as El-Hani and Emmeche (2000) point out, it would be wrong to conclude from this that vitalism was out-dated in favour of today's mechanicism. Mechanicism in this controversy is closer to organicism rather than the mechanistic approach that is the equivalent of physical reductionism.

material components of life, e.g. synthesizing urea by using chemical elements derived from the non-living. In the nineteenth century, emergence was addressed in line with the consequences of evolutionary theory (Corning, 2012). One of the main areas of concern was evolutionary novelty, that is, the possibility of the emergence of qualitatively different traits, and above all, the evolution of mind. For some theorists, Darwin's gradualist approach could not sufficiently explain the emergence of new levels of organization, so they developed their own theories of emergence as part of a holistic approach to the organism. However, emergence was overshadowed by reductionism with the advance of genetics from the 1920s, as the molecular explanation was preferred over the organicism (Corning, 2012). Thus, the problems of organizational novelty and increasing complexity have been superseded.

The discussion since the nineteenth century has involved a controversy between reductionism and this time, instead of vitalism, ontological emergentism (Emmeche, Køppe, & Stjernfelt, 1997). The new questions concern whether the explanation of biological or psychological phenomena can be reduced to physics, and whether the physical properties are predictable. Biological and psychological phenomena are associated with the emergence of "a whole kind of beings" (Emmeche et al., 1997, p. 91), such as the emergence of mind from the physiology of brain (Kim, 1996). In the context of the reducibility of biological and cognitive phenomena to physics, the properties that are thought to be emergent could be addressed as specific arrangements of matter. For example, the human body mainly consists of the elements of carbon, oxygen, nitrogen, and hydrogen, and it is obvious that only a specific configuration of these elements in a living organism enables metabolic activities, or cognitive functions, which are claimed to be emergent. Thus, the problem is due to the organization of matter. Wimsatt (1997) supports this account by pointing out that emergence primarily concerns the rearrangement of parts, as the alternative configurations of the parts lead to emergent properties. He adds that this does not contradict material reductionism. A specific configuration, which is the biological system in this regard, is emergent in the sense that the organizational context, as an actual type of configuration, cannot be directly predicted either by defining the physical nature of the constituents, or by considering the laws of nature determining the behaviour of these constituents. This approach makes room for emergence due to the complexity of systems, which is sometimes called weak emergence (Bedau, 1997, 2002).

A similar view has been defended in the constraint interpretation of emergence, which was introduced by Polanyi (1968) and held by other authors such as Pattee (2012). This interpretation depends on “the non-derivability of actual states from possible states represented in the physical laws” (Blachowicz, 2013, p. 22). According to this view, boundary conditions are imposed on the laws of nature, either as a physical boundary or as specific rules of mechanism (Pattee, 2012). For example, the chemical components of biological systems are subject to the laws of nature, but what determines the biological system is the morphogenetic condition that constitutes the boundary. Another idea in this view is that higher-level principles control lower-level activities because organization determines the circulation of physical components in biological systems. The boundary conditions of a complex system are emergent because these conditions are contingent and not determined by the laws of nature. On this basis, Blachowicz (2013) points out that the laws denote a possibility space depending on the initial conditions. This implies that the laws of nature must be understood as restrictions in a system, yet they cannot determine the actual condition in which these restrictions apply. Blachowicz’s approach can be applied to historically emergent characteristics of species due to evolutionary contingency. For example, an elephant cannot fly, and the fact that the elephant’s anatomical state does not promote the potential can be understood in relation to the laws of physics. On the other hand, the anatomy of the elephant is one of the countless potential forms within the possibility space that is dependent on the laws of physics, and in this sense, as an evolved form, it is historically emergent.

This approach is based on a distinction between the laws of nature as the basis of necessity and historicity as the basis of contingency; hence emergence is a consequence of contingency. Nevertheless, the constraint interpretation also holds that laws and actualization of causal processes are not completely distinct. As Blachowicz (2013) notes, laws can have varying degrees of generality. An example of this is the Kepler’s law which states that all planets in the solar system have elliptic trajectories. This is a law that emerges due to the relations between planets. Planets are objects in space, and this law is an expression of regularity due to the nonlinear relations between these objects. The elliptic trajectory is a derivation from more general laws of physics, but it appears as a new constraint due to the specific actuality of the system in point. In this sense, it can be argued that it is always possible to seek more universal grounds for the laws that apply to a system, as is evident in Newton's laws of gravitation compared to Kepler's laws. However, the search for a more inclusive basis of laws does not rule out the case that new constraints emerge locally, which means that laws that are specific to the system can be analysed by considering both the universal context of necessity and local application of contingency. In the light of this, the constraint interpretation of emergence can be formulated as follows. The local emergence of laws within subsystems denotes relational necessities, but the law-like expression of necessities is not merely a derivation of more inclusive laws because the latter cannot imply the former without historicity. As will be shown in the following sections, this dialectical relation between contingency and necessity is essential for understanding the form of the organism as a relational system that is extended in time.

In this context, my focus is the emergence of new relational patterns within an evolving system, which was discussed in the first chapter in relation to the emergent nature of the biosphere. In other words, this is the problem of the increase of complexity, that is, how it is possible that higher levels of complexity are generated out of the lower levels. For example, the beginning of life is a problem that reflects this type of emergence. The laws within a nonlinear system are path-dependent, which implies that they emerge through the evolution of complexity within the system (Mitchell, 2000). This is why the historical development of a system is latent with new boundary conditions, hence new possibilities. In other words, physical evolution of a nonlinear system develops its own necessities and possibilities. New boundaries emerge within the system historically, and once they emerge, they become the basis of systemic relations by constructively limiting the new conditions of complexity. An account based on the historicity of laws is proposed by Mitchell (2012). She argues that there are no universal laws. Laws are determined locally within the evolving subsystems, and this is the basis of increasing complexity in the universe. In this sense, not only biological organization, but also the laws of physics are emergent (Mitchell, 2000), hence the common basis of emergence in biology and physics is the universal evolution of complexity.

The second aspect of emergence that I discuss relates to micro and macro states. This is a question that is more directly related to the self-organization in ontogeny. Originally, emergent properties at macro level refer to the qualitative nature of the system that is irreducible to a certain microstate, but a more fundamental phenomenon that underlies this is how qualitative properties emerge from quantitative changes. The aggregation of particles has properties that none of the particles possess prior to this aggregation, which is why new properties at a higher scale are considered emergent. As expressed in the title of a highly influential paper by Anderson (1972), “more is different”. Physical properties such as colour and surface tension do not exist when there are only a few molecules. This is an ontological issue, which means that, it is not a problem due to empirical difficulties at a lower level, rather these properties simply don’t exist without the aggregation of multiple particles.

Bedau (2002) claims that an argument for emergence depending on macro-level properties is questionable because macro and micro levels are in fact ontologically identical. According to this idea, any property due to aggregation at the macro level is associated with weak emergence. Bedau (2002) gives the example of an ocean wave which demolishes a sand castle. In this event, weakly emergent macro cause is nothing but the iteration of micro-level causes at a different level (Bedau, 2002, p. 36). It is true that only the accumulation of molecules creates certain properties, say, a few molecules cannot create a wave. On the other hand, what emerges due to aggregation of components is a property that can be investigated both at micro and macro scales, and macro-level properties are not different from the perspective of micro-level analysis. Therefore, it is claimed, there is no macro-level property that is inexplicable at the micro level because the real distinction is between aggregate versus singular forms of particles. In fact, the emphasis on the physical identicalness of the macro and the micro is just another way of articulating an objection due to the synchronic nature of the emergent properties.

According to a contrary view, macrostate properties are still emergent because the behaviour of the mass at the macro level is not completely determined by a certain microstate (Wilson, 2009). Quantum level properties such as the spin of particles are eliminated in the analysis of macro-level properties in classical mechanics. Certain properties that characterize a specific microstate are functionally irrelevant to the ones that are measured as variables at the macrostate, as the probabilistic values of the micro-level properties average out each other (Wilson, 2009). As was discussed in the first chapter, a similar point concerning the emergence of order at a macro scale from disorder at a micro scale was made by Schrödinger (1967/2013). An underlying factor of this kind of macro-level emergence is the individuation of an entity as developing from the organization of its particles. In a solid body, the particles are constrained together in a way that leads to a loss of degrees of freedom. In this kind of individuation that depends on an equilibrium state, compared to a disordered aggregation of particles, the body is not dependent on the initial condition, as it acts as a stable attractor. On the other hand, it is claimed that this account of emergence is a matter of explanation, but not causation, because the elimination of micro-level properties implies an extraction of theories (Wilson, 2009). According to this idea, the theory (quantum mechanics) for micro-level phenomena lacks a full explanation only for the empirical reasons, whereas the theory that explains the macro level (classical mechanics) is instrumentally favoured, and in fact complementary to the micro-level explanation.

Reductionist explanations of emergent phenomena usually focus on mechanistic explanations of a causal transformation, and this usually relates to a precise micro-level analysis depending on localizing specific causal interactions underlying functionality (Bechtel & Richardson, 2010). On the other hand, Collier (1993) claims that localizing mechanisms has limits, and macro-scale emergence is a matter of causation beyond a problem of theory reduction. In a system with multiple chaotic attractors, arbitrarily proximate points can evolve into different attractors, and therefore “it is impossible to localize the boundary between two attractors" (Collier, 1993, p. 7). Cohesiveness at the macro scale is causally insensitive to micro-scale fluctuations, since any randomness at the molecular level is eliminated within the attractor states due to averaging of the lower-level random collisions. As a result, specific identity of the macro-scale object is not perturbed by these collisions, and interactions of the macro scale occur based on distributed properties.

A condition that has a particular importance for biological systems is the multiple realizability of the macro-level function. A macrostate condition is multiply realizable by a set of microstates, which is also the underlying idea of Boltzmann's well-known formulation of entropy. Most of the biological systems have this type of robustness due to multiple realizability, which can be considered a condition of the macrostate determination. Organizational robustness might appear because of several mechanisms such as the reorganization capacity of causal networks and many-to-many relations between structure and function, which is also known as degeneracy (see Section 3.2).[45] Also, since the organisms involve enzymatic activities that enable both the constant reproduction of their own parts and their capacity for regeneration to a certain extent, their macrostate is not only insensitive to micro-level perturbations, but it can moreover tolerate the loss of some of its parts. On the other hand, one could argue that the multiple realizability of biological functionality does not necessarily involve diachronic emergence because a specific function does not imply an equivalence of causal mechanisms that are able to perform the function. A definite answer to this question requires a comprehensive discussion of functions and causes, which goes beyond the remit of this work.

The final context of emergence that I will discuss in this section, which I think is the most essential aspect to understanding the diachronic nature of the problem, is due to part-whole relations. This relates to an old question of whether there is a causal capacity in the whole that is beyond the sum of its parts. As discussed above, specific configurations of the parts lead to emergent properties. Without biological organization, carbon, nitrogen, oxygen, and the other elements that

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[45] As will be shown in the last main section of this chapter, in biological systems, multiple realizability has a wider basis in the potentiality of regulatory networks.

normally constitute the organism are lifeless. The organization that is due to the dynamic relations between parts gives the whole its emergent characteristic.

Certain properties of matter are not merely resultant, but qualitatively different. Water has properties that neither hydrogen nor oxygen has by itself. A similar situation appears in downward causality through levels of interaction, which was discussed in the previous chapter. According to this, a higher-level property arises depending on the relations at a lower level, which then feeds back on these relations. A highly influential review that criticizes these notions is developed by Kim based on a distinction between synchronic versus diachronic understandings of emergence. Kim (1999) argues that an emergent property should be functionalized (p. 10). This implies a causal explanation of the system's transformation that leads to the emergent property. On this basis, he claims that emergent properties can be reduced to an explanation of inputs that create certain outputs. Downward causality is the causal influence of the whole over the parts, and supposed to be emergent, but Kim objects to this by stating that downward causality is a case of synchronic causation. For example, a bird can fly, and its different parts gain the capability of flying in the whole, whereas none of these parts possess the ability of flying (Kim, 1999, p. 30). However, he argues, the relation between the whole and parts in this kind of situation is synchronic because it is a compositional relation. The whole as compared to the collection of parts is not diachronically emergent because they are in fact the same thing.

Downward causality is considered synchronic with the composition of parts in Kim's explanation. If the additive effect of the parts within the whole is also assumed as effects for each part, this will imply self-causation, which is thought to be "an apparent absurdity" (Kim, 1999, p. 28). Thus, Kim's reference to synchronic causation implies a refusal of a type of causation that is deemed problematic. In fact, instead of a problematic mode of causation, it is stated that the synchronic context of emergence does not actually refer to a causal relation, as there is no causation actualizing in time (Emmeche et al., 1997). Kim's argument does not rule out all possibilities for emergence, as emergence is also addressed as a diachronic phenomenon. In Kim's account, however, there is no place for diachronic emergence, either, because the emergent property is considered a functional derivative of the inputs. Mitchell (2012) objects this by stating that this point is not enough to refuse emergence. She argues that the self-causation which Kim found absurd is in fact a common feature of biological systems, as they are determined by self-organization and feedback. She gives examples of emergence from the self-organized behaviour of the organisms living in colonies, in which higher-level properties emerge due to feedback relations within the system. Similarly, abrupt changes in cellular activity are due to positive feedback that creates a threshold response (Mitchell, 2012, p. 181). In fact, I discussed similar examples in the previous chapters in order to vindicate this viewpoint of self-organization, and therefore I believe that Mitchell's criticism is fair. But I also find Kim's emphasis on the synchronic nature of emergent properties useful. As will be discussed in the third main section, Kim's remark contributes to my distinction between diachronic and synchronic contexts of emergence.

I stated before that emergence can be properly defined only by considering the aspect of temporality. Anjum and Mumford (2017) insist on the ontological meaning of emergence in relation to temporality. They state that "the coming together of the parts to form a whole involves a transformation of the parts through their interaction" (Anjum and Mumford, 2017, p. 7). They emphasize that the emergence of downward causality is a matter of causation beyond constitution, as the whole gains an autonomous capacity over its parts. Downward causation emerges within a system, and transforms the parts in a context-dependent way. As a consequence of this process, the whole has an emergent nature. Anjum and Mumford (2011, 2017) mainly discuss emergence, not self-organization, but they point to the common basis that emergence is a matter of temporality, which is a crucial aspect of the issue. Furthermore, they oppose the Humean understanding of causation that suggests a cause diachronically precedes its effect. In their view, cause and effect are synchronic, as they both extend simultaneously, and the exhaustion of the effect takes time. Based on this, they rule out the claim that emergence is epiphenomenal. Recall that one of the key points in the critique of emergence by Kim (1999) is that there is no involvement of causation in the synchronous part-whole relationship. Since Anjum and Mumford (2011) argue that causal relations are synchronic, in their perspective, there is no reason to assume that synchronicity of composition is exempt from causation. On the contrary, “emergent properties are sustained through the on-going activity; that is, through the causal process of interaction of the parts” (Anjum & Mumford, 2017, p. 9).

Nevertheless, the main premise of this argument that cause and effect extend synchronously is controversial. Hansson Wahlberg (2017) criticizes their account of synchronous causation, which presumes that cause and effect are instantaneous. He notices that this implies that no passage of time is required between the cause and the effect, which contradicts the principle of special relativity that nothing can propagate faster than the speed of light. Therefore, according to him, Anjum and Mumford’s (2011) claim that causal powers pass around spatial distance cannot be true. Hansson Wahlberg (2017) also suggests that if sequential causation is dismissed, objects can have no powers. A final verdict concerning Anjum and Mumford’s argument would require a discussion in the context of the relevant theories in physics, whereas this type of discussion concerning the nature of causation is beyond the scope of this work. On the other hand, although the abovementioned criticism demonstrates that there are certain explanatory gaps in Anjum and Mumford’s argument, I think their remarks can still be useful. I will return to their argument in the last section, and defend a revised version of their view on causal relations that does not necessarily involve a synchrony between cause and effect. Concerning emergence, Anjum and Mumford’s claim highlights the diachronic aspect of the problem and the transformative role of downward causality. In this sense, their theory offers support to the processual account of organization.

Emergence in part-whole relations is a problem of dynamic relationships. In terms of a static understanding of part-whole relations, the whole is an epiphenomenal term that implies a specific composition of parts. At first glance, emergence can be denied despite a process approach to this compositionality. One can argue that nothing is emergent because the outputs that are supposed to be emergent are deterministic consequences of the inputs (which I have suggested is implicit in Kim’s argument), as the sum of components and interrelations are reducible to these inputs. For example, concerning the wholeness of an organism, developmental processes, physiological activities, or cognitive processes can all be considered as responses to specific inputs, either as short-term effects such as stimulation or as long-term effects such as the “genetic codes”. It follows from this perspective of mechanical predeterminism that the emergent nature of causal processes would be easily superseded. Yet, I believe that this kind of aggregation-based consideration of the system as the parts plus interrelations will result in a misleading approach that strips the system in focus from its temporality, and that ignores the synergetic consequences of the internal relations. The abovementioned approach of composition disregards one crucial detail. When something is defined as a whole, this refers to a determinate thing with a form. However, the determinateness of the whole consists in a dichotomy between the form in its frozen state and the form in its constant dynamism. A conception of part-whole relations that is limited to composition is dependent on the notion of an object with a strict form directed toward a certain trajectory. This does not provide an adequate understanding of the internal dynamism of the organism. In the case of organisms, the form is dynamic, as the whole is determined by a complex network of feedback relations. This makes the issue inconsistent with a static account of compositionality and a neat analysis of inputs that contribute to the emergent properties, which brings us to the problem of dynamic form that I address below.

2. The Form of the Organism

Diachronic emergence paves the way for a radical ontological ground for self-organization in so far as it shows emergence is not merely a problem of composition. However, describing the concept that way does not offer an ultimate solution, but only brings the problem into a new dimension. As discussed above, the main difficulty is the paradoxical implications from the synchronous condition between emergence within a system and the parts that constitute the system. A possible solution lies in the dynamic form of the organism, which involves the idea that the organism’s form extends over time. In the following sections, I will discuss specific problems of the organism’s dynamic form. The first problem is hylomorphism, which denotes a dual approach to an entity based on matter and form (Section 2.1). The second problem is relationality in the context of contingency and necessity (Section 2.2). The third problem relates to two theories that propose opposite explanations for the organism's form, which are genetic reductionism and developmental systems theory (Section 2.3). The aim of discussing these issues is to examine how the notion of form is understood philosophically, and how different approaches are applied in biology, which will provide a basis to develop my own perspective on this issue. My main argument is that the organism's form has a relational basis which is determined by the response of the organism towards both internal and external contingencies. Relationality denotes a basis of necessity that emerges between different variables, which is in fact a different way of expressing the constraint interpretation of emergence that has been explained in the preceding section. Furthermore, there is a constant potentiality in the dynamic form, which makes the self-organization of the organism different from non-living self-organization that is temporary.

2.1 Hylomorphism

Form can be explained in different ways, namely, as an abstraction of the structural properties, a precondition of individuation, a type of organization performing a specific function, etc. In this section, I will focus on the idea of formal cause, as it is a notion that is often appealed to as an explanation of downward causality, the emergent nature of biological organization, and self-organization (e.g. Delbrück, 1971; Rosen, 1991; El Hani & Emmeche, 2000; Moreno, 2000). Despite the widespread appeal to formal cause in these diverse explanations of life's organization, the extent to which these accounts accurately portray the original ideas, or even the original questions, is questionable. In the context of Aristotelian philosophy, formal cause explains the form as a way of shaping the potentiality within material cause, although form is not a distinguishable element in a real entity. Hylomorphism, which is a concept that originates from the words *form* and *matter* in Greek, expresses this duality. Below, I will discuss the explanatory value as well as some potential problems of this Aristotelian notion in the context of its application in modern approaches towards the organism. It seems that there are two main problems. Firstly, the modern scientific approach is based on efficient causes, which is why reconciling Aristotle's pluralistic account of causation with the one-dimensional modern approach would be problematic. Secondly, it is not clear that the formal cause can be applied in isolation from the broader cosmological claims of Aristotelian philosophy (Hulswit, 2005). The formal cause is applicable due to its connection to teleological explanation, since it is closely related to the final cause in this approach. On the other hand, organization refers to a dynamic structure with a function, and this in turn implies a question of purposeful activity. Also, it is true that modern approaches to the organism are not always hostile to teleology, as there are cases where purposeful activity is considered necessary for organization (Pittendrigh, 1993) and teleology is reformulated within materialist approaches (Monod, 1972). Nevertheless, this is a limited purposiveness localized in the organism. It should also be noted that final cause is a concept beyond purposiveness (Falcon, 2015), as it is originally defined in the face of the question of why something has occurred, which is an issue that relates to both living and non-living systems. Furthermore, contemporary understandings of self-organization are inconsistent with the cosmological underpinnings of Aristotelian hylomorphism, since the former interprets final cause or any equivalent of the final cause due to local dynamics, whereas the latter acknowledges this only in a universal context.

In the Aristotelian view, the form refers to the shape of an entity as opposed to its material. In a well-known example given by Aristotle, the form of a bronze statue is due to what is made from the bronze: formal cause is the shape given, and material cause is the bronze (*Metaphysics,* trans. 2016). This notion of form as distinct from materiality provides a basis for the modern concept of organization and the relational properties that are applied to matter as abstract qualities (DiFrisco, 2014). For example, the qualities of the living system which are associated with minimal conditions of life, e.g. metabolic closure, homeostasis, compartmentalization (although a controversial one) are structural properties that apply to all living systems. In a more specific approach, form can be associated with functionality, e.g. the form of the fin of a marine animal that is convenient for its swimming function.

Aristotle’s understanding of form can be interpreted as a dynamic condition that is crucial for biological organization. Concerning living things, Aristotle defined the form of the organism as to what is essential to its organization, but not due to its static shape at a certain moment. According to Aristotle, “matter is potentiality, while form is actuality” (*De Anima* 412a9). The soul of a living thing is its form, and it is an actuality of the natural body (412a22). Moreover, formal cause is consistent with the modern conception of organization due to its connection with functionality, since it is closely linked with final cause. Final cause internally determines self-moving entities in line with a mature actualization of form, as a seed has the potentiality to grow to become a tree (412b27).

In this respect, Aristotle's distinction between types of causation seems applicable in terms of the modern approaches to function and organization. However, there is no consensus among contemporary references to formal cause on how different types of causes relate to each other. Rosen (1991), who tried to formalize the structural basis of the organism depending on category theory, argued that formal cause must be reconsidered to overcome the limitations of the Newtonian science and its basis in efficient causation. He claims that the organism is closed to the effects of efficient causes due to the relationality of its structure. According to him, the initial conditions of a system are equivalent to material cause (Rosen, 2000). In response to Rosen, Pattee (2012) identifies how the initial conditions are also a matter of measurement. One should not ignore the context where a measurement is chosen by an agent, and thus there is a teleological and subjective element in the measurement. The interpretation of Aristotle's four causes also differs in other interpretations. For example, López-Moratalla and Cerezo (2011) define biological identity as the increasing form, which implies that form is acquired (similar to the emphasis of DST), and claim that efficient cause and formal cause are unified in the material causation of the organism, whereas Salthe (1993) emphasizes the connection between final cause and formal cause in relation to the organism's individuality. In another interpretation, Emmeche, Køppe, and Stjernfelt (2000) propose applying an Aristotelian account of causality by replacing final causality with functional causality. These views are generally developed by emphasizing multiple levels of organization, but formal cause is also used to support the contrary position of gene-centric explanation. Delbrück (1971), who is the inspirational source of Schrödinger's preformationist concept of life, has claimed that genes represent the Aristotelian notion of unmoved mover. The unmoved mover is a concept which denotes something that moves other things without itself being moved (*Metaphysics*, trans. 2016). However, this seems to be a misinterpretation of the original idea, as Aristotle’s notion depends on a downward determination of the form due to final cause, but not an upward determination as suggested in genotype-phenotype mapping.

In these modern interpretations of formal cause, form is usually associated with the emergent aspect of biological organization and the role of downward causality. Although these aspects are significant in terms of understanding self-organization, a serious drawback emerges from appealing to formal cause in relation to downward causality, as pointed out by Hulswit (2005). This criticism focuses on the potential difficulties with the applicability of the notion of formal cause because of the wider implications of the worldview that this notion originates from. First, he calls downward causality into question, which has certain parallel aspects with Kim’s (1999) approach. Hulswit (2005) claims that downward causality is problematic when it is taken as a causal principle. A global pattern that emerges in a system does not really create a causal effect on the parts, since the whole is already identical with the parts. Therefore, according to him, what is meant by downward causation is in fact “downward determination” (Hulswit, 2005, p. 282). The criticism of formal cause is developed on this basis, as the form is in fact a way of determination. Theories about formal cause should not bypass this distinction between efficient causes and formal determination. He points out that in today’s science, causal interactions, including the ones that are attributed to downward causality, are explained due to universal laws. There is a sharp contrast between the Aristotelian plurality of causal explanations and the modern-era mechanistic explanation based on the laws of nature. Therefore, he argues, one cannot apply the Aristotelian solution without dealing with the ambiguities this introduces because of the inconsistency between these two worldviews.

Hulswit (2005) acknowledges that downward causality and formal cause might have a role in an approach that is alternative to what he calls “the substance addiction” of Western philosophy, which ignores the processual nature of things (p. 283). Yet, he calls attention to the fact that an emphasis on formal cause also implies a fundamental change in our perspective on causation, and without dealing with this, the Aristotelian notion of form cannot provide a solution in a scientific world in which only efficient causes are recognized. He criticizes using the concept of self-organization in biology on the same basis.

Can Aristotle's formal cause be a basis for the organism's self-organization? Matthen and Hankinson (1993) point out that "Aristotle's universe is a self-maintaining structure" (p. 425). Contrary to the modern scientific approach that explains the properties of the whole by appealing to the properties of the parts, Aristotle's explanation is anti-reductionist since the form of the whole determines the parts (Matthen & Hankinson, 1993, p. 426). The parts affect the whole, too, but this takes place by the material causation, which is subordinated to formal causation. The change in the form is triggered by the incongruence between things' ideal location and current location. Thus, things tend to their place, i.e. they move in order to realize their idealized condition, which is a reflection of final causation. Time is conceptualized through motion, and motion occurs due to *telos*, which is essential for finalizing the hylomorphic unity in an entity. Temporality is involved as a part of the explanation due to final causation, hence the question of dynamic form is implied in final causation. There are answers for the problems of form and change, once the underlying final cause is understood. On the other hand, it is important to note that final cause is not necessarily due to the aims of purposeful agents, but it is the cause that refers to the question of for the sake of which a thing has come to be (Nussbaum, 1978; Vinci & Robert, 2005, p. 211).

Van de Vijver (2013) points out that in Aristotle's philosophy, there is the developmentalism of the one, whereas in Evolutionary Systems Theory and modern theory of self-organization, there is the "developmentalism of the many" (p. 248). In the former, the role of chance and spontaneity in the production of living things is precluded, and form is determined in a cosmological hierarchy which is ultimately determined by final cause. However, according to today's understanding of self-organization, development is inherently contingent (Salthe, 1993), and the structure cannot be a full, undistorted expression of the form. Therefore, Van de Vijver concludes that the Aristotelian view is not a self-organizational one. I think this interpretation of Aristotle shows why formal cause is not consistent with the levels of organization in the contemporary approach. In Aristotelian philosophy, there is room for self-organization, due to the self-motion of animals and to the idea of epigenesis (see Section 3.3). Yet, these are all based on a universal teleology. So, Aristotle's account supports a cosmological self-organization, and local self-organization only exists in so far as it is included in this universally complete teleology. Modern theory admits that matter has the capacity to organize at all scales, but the relation between the local and the more inclusive levels are not necessarily associated via the final causation. In this sense, the modern approach might involve a unity of self-organization as a network of ecosystemic "islands" which all have their context-dependent transformations, as their self-organization is dependent on constraints that appear locally in developmental processes.

In another interpretation by Rieppel (1990), material and efficient causes are considered as proximate, realized in ontogeny. Whereas formal and final causes are in line with functional explanation, that is, tinkering with the generated structures in accordance with natural selection. This approach seems to provide an interpretation that attributes a global scope to the formal cause and a local role to the efficient cause. However, this approach does not really reflect the Aristotelian view. For Aristotle, it is not evolved traits, but self-motility, that is tied to a universally forming principle. Thus, even though the causal influence of natural selection with shaping the organism's form might be justifiable in its own way of thinking, one should also consider whether this really reflects the initial philosophical issues that were addressed in relation to the notion of formal cause.

The endorsement of four types of causes usually originates in the criticism of mechanistic explanation. Witherington (2011) states that in modern science, which is influenced by Newton and Descartes, positional identification and prediction of an object's trajectory are the main commitments of causation. Yet, this attitude is challenged in favour of a causal pluralism in new approaches such as general systems theory. According to the Aristotelian four causes, form and function are considered in the context of a thing's coming into being. The four types of causes, according to Witherington, are different ways of abstracting patterns, which suggests that causal pluralism is in fact a matter of explanation: "Formal and final causes do not cause the way efficient causes cause . . . but order our sense of the directional flow of development" (Witherington, 2011, p. 74). In this way, the problem leads to the old dilemma between causation and explanation. Claiming that four causes do not indeed cause, but “order our sense” suggests a similar position to Kant’s claim that teleology is not a constitutive, but a regulative element (Kant, 1790/2008). In this regard, the main disagreement is whether the four causes are explanatorily reducible, that is, whether formal cause can be reduced to efficient causes, or it is irreducibly complementary. As a view that can be interpreted as in favour of the latter, Pattee (2012) says that different ways of explaining the world, such as deterministic versus statistical explanation, or necessity versus chance, are complementary, implying that both sides of the conceptual distinctions are necessary in order to explain natural phenomena. Can we say that matter and form, or Aristotelian four causes, are complementary in a similar way? Or, shall we retreat to a position that, similar to Kim’s (1999) attitude towards emergence, formal cause is epiphenomenal, that is, an explanation due to the formal cause can be reduced to an explanation due to the efficient cause? The answer depends on how we contextualize form in regards to biological organization. In the following section, I will try to answer this question.

2.2 Relationality and contingency

In this section, I focus on the structuralist context of form.[46] According to structuralism, form is the abstract pattern that is represented by a relational model, which is usually thought to be mathematically analysable (Goodwin, 2000). Since structuralism is regarded as an approach that justifies the formal cause (Rosen, 1991), philosophical issues concerning this Aristotelian idea must be clarified. In the previous section, I dealt with some problems surrounding the Aristotelian origins of formal causation, i.e. referring to formal cause without addressing its broader relation to Aristotelian cosmology, and the inconsistency between the Aristotelian worldview and the modern theories of self-organization. As the central question in my discussion concerns the form of the organism, but not Aristotle’s formal cause, the main idea behind formal cause that form is the precondition of an

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[46] There are various approaches to form in the contemporary analyses. The understandings concerning information contributed to these alternative approaches. For example, in the semiotic analysis that is based on Peirce’s triadic systems, form refers to signs that are not matter itself, but the representation of matter (Queiroz & El-Hani, 2006). This concept of form is put forward by considering the relationship between the sender and the receiver of information. Different contexts of form are not necessarily mutually exclusive of each other; instead, they are different applications of the relevant philosophical idea that goes back to the Platonic notion of form.

individuated system can be re-contextualized by opposing its bipolar hylomorphic context in which form and matter are the complementary notions that underlie real entities (Simondon, 2009). Form and matter are indistinguishable aspects of individuation, whereas they are subjectively distinguished depending on the analysis of organizational complexity. Based on this idea, I make a further claim: I argue that matter cannot be dissociated from its organizational context because relationality determines the nature of things. Not only the biological, but also the physical is dependent on organization. Therefore, what is identified as the matter that is formed through organizational context is in fact nothing but a label that disguises where analysis stops revealing the relational basis of things by decomposing the organization further. As will be shown in the third section, this radical conception of relationality is essential to acknowledge the emergent nature of the organism. After making these claims concerning relationality, I focus on the relation between contingency and form with respect to the historicity of biological systems. This will serve as a basis to criticize a pure formalist interpretation of structuralism that reduces the organism to abstract relationality. The main issue that I deal with here is the evolutionary aspect of contingency, which is necessary to understand the ontogenetic aspect of self-organization. There are two points that I emphasize. First, contingency is an irreducible element in the form of a system,[47] and second, structure should be considered in the context of abstract necessities within interdependency relationships.

A main theme of the structuralist approach is the relational properties that appear as interdependent features of organisms. For example, allometric relationships that consider the ratios between anatomical parts or other relations such as the one between the metabolic rate and the size of the organism are in this category. These relational properties are also investigated across phylogenetic differences. Comparative anatomy deals with the morphological similarities and differences between species. From the structuralist perspective, comparative analysis must consider the appearance of a Bauplan, which refers to a consistent

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[47] In fact, that contingency is an irreducible element of biological organization was already pointed out in the previous chapter. The discussion in this section can be considered as a continuation of this argument in relation to form.

set of morphological traits. The notion of Bauplan implies that robust forms persist through evolutionary change, or the evolutionary path tends to converge to formal robustness. In comparative analysis, functional explanation considers the adaptive nature of certain traits and why they are selected individually, while leaving the issue of diversification of these Baupläne merely to random mutations. On the other hand, another research tradition that is represented by biologists such as D'Arcy Thompson has emphasized that form is constrained by certain developmental and physical constraints. For this reason, the evolution of species is not due to the exploration of a continuum of potential forms in which traits can co-exist within any combination, but on the contrary, only certain types are involved as consistent forms in the possibility space of evolution. In a pre-Darwinian conceptualization, these generative principles were referred to as the laws of form (Denton & Marshall, 2001).

There are two elements that I believe to be important within the structuralist approach. The first one involves the physical basis of form, as the laws of physics determine the consequences of certain sets of features. For example, as the mass of an animal increases, the ratio of the thickness of bones to the bodyweight that is required to hold the animal becomes higher, so that the bone has to be proportionally thicker. This is a direct consequence of the law that the gravitational force on the animal increases exponentially as its mass increases. Second, the construction of the form is relational and processual, appearing as the constraints of the morphogenetic field. Consequently, what makes the whole possible as a Bauplan depends on whether it is a consistent developmental process. Thus, a partial characteristic can only be involved in a consistent form, but not in any type of combinations. These two points are crucial to understand why form is a matter of the lifespan of the organism. Considering form as a consistent developmental process has implications that lead us to appeal to the idea of morphogenesis. This connection will be examined in the following sections.

How should we understand the physical basis of relationality? DiFrisco (2014) remarks that the models of living systems begin either with matter as constituting the basis for a bottom-up approach, e.g. the definite conditions of life such as biomolecules, or with form as the basis for a top-down approach, which refers to the abstract relational properties of life. I believe that this is basically true, except the fact that "matter" is contextual, too. This means that what is defined as matter such as biomolecules can also be subject to a relational analysis, as the decomposition of part-whole dynamics can go further down the levels of organization. For example, carbon is an element that is involved in biomolecules. It is not exactly appropriate to consider carbon atoms as matter vis-à-vis biological organization, which depends on the relations higher than the atomic level. Considering atoms as the matter of the system as opposed to levels of organization only means that the analysis of organization stops at the atomic level without going into the sub-atomic level, acknowledging the latter under the cover of the physical properties of carbon, e.g. carbon is an element that is capable of making four covalent bonds, the most common isotope of carbon in nature includes six protons and six neutrons, etc. However, ontologically, the physical properties of carbon are a manifestation of organization at the sub-atomic level, as the capability of making four covalent bonds in this case is determined by the orbital structure of the electrons, which is a matter of organization as well, since it is determined by the internal relationality of an atom.[48] All there is in the world that is known as matter has an organizational context, and this is why things are nothing but their relations. Therefore, a structuralist attitude towards form does not necessarily depend on a certain level as a distinguishable dimension of matter aside from biological organization, but it is based on focusing on the relational necessities that are imposed on sub-level components.

An abstraction of this relationality implies that the structural basis of organization is not limited to certain material components, or certain historical appearances of species. However, this does not mean that there is a pure form of abstract relationality that can be examined without considering the actuality of living systems. Concerning the tension between the abstract and the actual, Rosen's (1991) attitude seems to represent an extreme bias toward the former. His

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[48] As a more telling example of relationality at the sub-atomic level, it is claimed that modern physics shows that sub-atomic particles have no intrinsic properties, e.g. a neutrino and an electron are actually the same thing in a symmetrical state, and they become differentiated only due to their relational context in the interconnected unity of the atom, as the electron's interaction with the Higgs particle gives its mass (Schlemm, 2003, p. 65, as cited in Smolin, 1997).

mathematical work, which was developed within elementary category theory, an area of mathematics that is used to map the transformations between sets, only considered this relational and abstract basis of form. Rosen (1991) criticized Newtonian dynamical analysis for being reductionist as it aims “to throw away the organization and keep the underlying matter”. In contrast, his relational approach intends to “throw away the matter, and keep the underlying organization” (Rosen, 1991, p. 119). Rosen’s main strategy to achieve this is by developing a purely syntactical language, as a sublanguage of scientific modelling within natural language that includes both syntactic and semantic elements (DiFrisco, 2014, p. 510).

Pattee (2007) criticizes Rosen’s approach for being extremely structuralist, aiming to get rid of materiality. He states that Rosen tried to reveal the abstract nature of self-replicating systems by ignoring the empirical aspect of this issue, as “he was not concerned with the possible material realizations of formal models” (Pattee, 2007, p. 2275). Pattee opposes this type of extremism and insists that a living system is an actual one, and therefore should be considered in a materialist approach in contrast with Rosen’s formalism. Pattee (2007) obviously refers to the empirical aspect of biology here, and in addition to this emphasis, I think we can also interpret actuality in relation to the historical context of living systems. An actual living system, in contrast with abstract schemes, establishes real relations with its environment. Thus, an understanding of ontogeny requires considering not only abstract interrelationality but also specific spatial and temporal settings of these real relations. Therefore, the historicity and actuality of a system is beyond the scope of a formalized analysis of temporality.[49]

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[49] As discussed in the first section, Blachowicz (2013) was making a similar argument about emergence by pointing out that laws of nature cannot determine historicity per se, and an element of contingency always needs to be added to the system in focus for the laws to operate. Within the theoretical tools that are used to analyse this historical entity, the laws of nature denote relational necessities, and the attribution to necessity suggests that, prima facie, they are unchanging and not subject to contingency. However, as a matter of fact, the precondition of necessity for relationality is also subject to historical change, since the laws that determine the consequences of relations are also products of a universal evolution that constitutes the background of all causal relations. This is based on Mitchell’s (2000) views on the laws of nature in many ways, and the implicit opposition of the distinction between ceteris paribus laws that are peculiar to “special sciences” such as biology and the laws of physics that refer to deterministic relations. But I will not go into the details of this argument.

The abovementioned approach can also be applied to evolutionary contingency. The form of a specific species is constrained by relational necessities that are the reflections of the laws of physics, but form is also a product of evolution. As emphasized by the evolutionary contingency thesis, evolution is primarily a historical and contingent process (Beatty, 2006). For example, an elephant's bones must be thicker proportionally to its size, which is a consequence of physical necessities. However, the elephant as an animal with bones and flesh, and a material entity that is actual in a specific time and location, is also a product of contingent historical conditions. In this example, biological contingency and physical necessity are relative: The former is contingent in so far as it is the theoretical field of a later stage of evolving complexity, whereas this does not entail that the latter is not also subject to historicity.

Is there a tendency in the approach of relationality and self-organization to get rid of the historicity of organisms? This is a question of whether referring to the universal, structural, and deterministic as opposed to accidental changes requires denying the role of the latter in the organization or not. There are different stances on this issue. I have mentioned Rosen's attitude, which is an extreme attitude based on abstract relationalism, considering form as exempt from historicity. Kauffman (1993) has also claimed that self-organization is an abstract characteristic, which involves a tendency for spontaneous order. Yet, his theory is based on an expectation of specific patterns of relationality that appear within actual systems which does not necessarily deny the role of historicity. Other researchers such as Newman and Goodwin, despite focusing on the structuralist aspect of organization in their research, have emphasized the role of contingent elements such as frozen accidents, which are the specific contingent events in the evolutionary history that determine the fate of later forms (Goodwin & Webster, 1996; Newman, 2003; Newman & Bhat, 2009).

The relational basis of self-organization can involve both the law-like characteristics of form, which I referred to relational necessities, and contingency that appears both in evolutionary history and in ontogeny.[50] Here, contingency

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[50] At this point, one might wonder why such a phrase as relational necessity is required, as there is already a notion called "structural constraints". As an answer, I refer the reader to the discussion on

refers to the accidental aspect of the form, which is not only due to factors such as frozen accidents in evolution, but also history-dependency of biological systems. Consider the lifespan of an organism. The form of the organism is never a perfect materialization of a Bauplan, but rather it is affected by multiple events through the organism's lifetime which might leave their marks on form as epigenetic differentiations. We cannot think of a Bauplan that is distinct from the contingent actualization of the organism it relates to, since contingent factors such as epigenetic differentiation are not necessarily a diversion from an exact form, but an inherent part of the form of the organism. We can speak of the potential states of form that precede specific contingent actualizations, e.g. the epigenetic mechanism of methylation that is capable of silencing or activating specific genes is there before any contingency actually appears. However, this potential in the organism cannot correspond to the form per se. Thus, relational necessities are imposed on a possibility space, which is why contingency cannot be eliminated. They cannot be addressed due to pure context-independent structuralism either because relationality is in fact realized as the tendency to form structures, or as the self-maintenance of already formed structures. Therefore, contingency is an unavoidable aspect of the organism's form. As Ramírez-Trejo, Demarest, Van Poucke, and Van De Vijver (2016) point out, "there is no form without history; no synchrony without diachrony; no being without becoming" (p. 370).

On the other hand, the critique of formal structuralism on the grounds of ignoring the role of contingency could fall into a straw man argument without clarifying the issue of temporality within organization. In fact, structuralism does not deny the aspect of temporality within organization on any account. An analysis of the structure can deal with the role of temporality that is abstracted from materiality, yet this involves a notion of time that is quite different from the historicity of a system within its actual relations with the world. The problem arises when the reflections of the historical context are ignored. Here, contingency refers to unprecedented events and the coalescence of several factors from multiple

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the constraint interpretation of emergence in the first section, according to which a constraint has both a law-like aspect and a contingency aspect due to the actuality of the condition. Due to this double-edged description of the constraint, I distinguish the aspect of necessity from a structural constraint.

sources of causation that make an exact predetermination impossible. I will discuss the role of contingency in biological processes more in the following section.

2.3 A critical analysis: DST, genetic reductionism, and structuralism

In the previous section, I discussed the ways that form is abstracted from material conditions, and how the structuralist claim is built upon this abstract organizational basis. In this section, I will address how the question of form is explained in different theoretical approaches in biology. Since the form of the organism is one of the main issues in this chapter, it is essential to justify the organism as a nexus of form from an organizational viewpoint. In other words, the question is what makes the organism special as a level of organization in which form is stabilized. There are multiple levels of biological organization from molecules to ecosystems. According to gene-centric explanation, genes are the origin of form, whereas developmental systems theory (DST) refutes prioritizing the genetic level by emphasizing the epigenetic and environmental aspects of inheritance. One of the main ideas of DST is that biological form is not predetermined by genes, but rather is acquired through systemic interactions. DST helps to acknowledge that there are multiple causal elements in the emergence of the organism's form. Nevertheless, its perspective is biased towards the contingent aspect of development as it ignores the relational necessity that was discussed in the previous section, which leads to an overstatement of the importance of contingency. Moreover, DST has been criticized for offering a holistic approach towards levels of organization (Godfrey-Smith, 2001; Van Speybroeck, 2000). These two criticisms converge on the deficiency of DST concerning the analysis of the stabilizing elements of organization. In the light of these remarks, I argue that neither the gene-centric approach nor DST provides a sufficient explanation for the peculiar dynamics of organization within the organism. These two approaches constitute a dichotomy between micro-reductionism in the former and macro-reductionism in the latter. After this analysis, I focus on another comparison, which is between DST and structuralism (also see Section 2). I propose reconciling the roles of contingency, which is emphasized by DST, and internal constraints, which is emphasized by structuralism.

Let me begin with the discussion of the gene-centric approach, which is objected for several reasons. The relevant criticisms state that only a small percentage of genes are involved in direct coding of proteins, most genes are part of regulative networks, and that the essentialist conception of genes is problematic (Griffiths & Stotz, 2006). Moreover, it has been shown that the morphogenetic nature of the organism can persist without the involvement of genes (Goodwin, 2001). The contrary approach of DST claims that the form of the organism is not predetermined or coded by genes, but acquired due to the developmental sources of several inheritance systems. The advantages of DST are that it is critical of the classical nature/nurture distinction, and that it promotes the importance of epigenesis. A main argument that is developed along these lines is that the life cycle is reconstructed due to self-organization of the organism (Griffiths & Gray, 1997). On the other hand, despite this positive contribution, the macro-reductionist attitude of DST (Robert, Hall, & Olson, 2001; Van Speybroeck, 2000) hinders the possibility of justifying this claim concerning self-organization.

According to gene-centric explanation, which was popularized by Dawkins (1989), genes carry the information that codes the organism. This view is criticized by different perspectives including epigenetics, systems biology, and morphogenesis. A main criticism targets the implicit claim that there are specific genes for each specific phenotypic trait. This is also reflected in popular considerations, such as in the “gene for obesity”, although this kind of phrase is far from reflective of reality. The biggest problem is that this specific understanding bears the traces of the Mendelian analysis that is based on correlations between the frequency of certain phenotypic traits and certain alleles in a population. Although several internal and external factors are involved in the expression of genes and the emergence of phenotypic traits, this Mendelian notion of a gene still survives in the “gene for X” way of thinking. According to the contemporary understanding, the underlying phenomenon in the idea of genetic coding is the formation of a three-dimensional shape of a protein out of the amino acid sequence. However, only certain parts of genes that are known as exons are encoded in RNAs, and the amount of genes that directly code proteins is even smaller. In most vertebrate species, genes that are coding proteins constitute only a small section of the genome. The proportion of coding DNA is so small in humans that it only makes approximately 1% of the genome (Venter et al., 2001; Moss, 2006), whereas it is now known that non-coding DNA usually has regulatory functions. These regulatory functions are performed by more complex networks that are highly dependent on other elements such as RNA. Basically, gene regulation is "encoded in the way the DNA sequence is folded up with proteins to form chromatin structures" (Boi, 2011, p. 206). Contrary to the idea that phenotypic traits are directly coded by genes, these properties are influenced by a complex interaction of several factors, including morphogenetic factors, cell-to-cell interactions, de novo formation of the organelles, epigenetic regulation, etc. Although some of the gene sequences can be associated with specific higher-level properties, this is almost never a one-to-one mapping between the genotype and the phenotype because a type of higher-level entity such as a membrane can be coded by a set of genetic sequences that consists of several different variations (Moss, 2003).

Genes are expressed according to their interactions with other genes, which means that their function is context-dependent within the genome. Therefore, an essentialist definition of the gene is problematic (Griffiths & Stotz, 2006). It is the interaction between the genes, cytoplasm, and signalling networks across the cellular membranes that determine the context of genetic expression. In this sense, self-organization at the organism level is antithetical to genetic reductionism. Moreover, genes are turned off or turned on due to epigenetic mechanisms, which are influenced by environmental factors. Two common cases of epigenetic regulation are DNA methylation, in which a gene is silenced by a methyl group, and histone modifications, which affect the quantitative level of gene transcription. Another reason that the gene-centric view is problematic is the self-organized nature of development. Certain regulatory genes are found in several multicellular species, suggesting that these genes have been kept due to their role in morphogenetic development. Thus, genes don't program the organism out of nothing, but they are part of a process in which physical forces are turned into dynamic patterns (Newman & Bhat, 2009; Newman & Linde-Medina, 2013). Furthermore, the experimental studies on *Acetabularia* have shown that morphogenetic development can occur independent from genes (Goodwin, 2001, pp. 78-83). *Acetubularia* is a huge single-celled organism living in subtropical waters. In these experiments, it is found that when the organism is split, the part of the organism which is without the nucleus, hence without genes, is capable of regenerating itself to a certain degree. This occurs as a process of dynamical patterning due to the calcium gradient in water. It is not possible to find similar examples in multicellular organisms that are more complex. This is due to the fact that morphogenetic patterning is not sufficient to establish form without the stabilization of genes (Newman, 2012). In summary, genes are the molecular sources of developmental pathways, which remain inert in the absence of other organizational processes. Hence, they are activated in a context-dependent way, and cannot be the sole source of determination for form.

Although it is claimed that genes constitute the formal cause of biological systems (Moreno & Umerez, 2000, p. 109), in the light of the ideas of Newman previously discussed, it is more appropriate to consider genes as the stabilizers of form. The notion of the genes as the formal cause leads to a preformationist conception of form. Goodwin (1987) remarks that preformationism based on genetic determinism reduces self-organization to a self-assembly process. In this kind of reductionism, it is supposed that “genetic program determines the molecular constituents of the organism”, and the interactions between these constituents are explained due to “short-ranged forces of crystallization and self-assembly” (Goodwin, 1987, p. 168). In this approach, material composition is supposed to determine the form similar to the spreading of crystallization (Schrödinger, 1967/2013; Delbrück, 1971; Monod, 1972). Goodwin (1987) refutes this claim, as it presumes a one-to-one organizational determination between the molecular-level and higher-level organization reducing a higher-level principle to the atomistic composition. This contradicts with the polymorphism at the molecular, cellular, and tissue levels of life, in which same atomic composition can produce different types of organization. Genes by themselves cannot act as the formal cause, as this would ignore the other dynamics of form at the higher levels. Moreover, organizational pathways are not one-to-one, but one-to-many.

Therefore, self-assembly plus genetic programming cannot be a sufficient explanation for biological form.

As a contrary view, DST explains development and evolution by appealing to a pluralistic notion of causation and by emphasizing that any kind of continuity, whether internal or external, can be a developmental source. It is argued that genes are not the only source of information, but any kind of contingent source, due to culture, constructed niches, epigenetic traits, etc., can be an input through the ontogeny of information (Oyama et al., 2000). DST does not claim that these sources contribute equally to the change of systems. Instead, it argues that inheritance is context-sensitive, as different inputs can be more prominent depending on the contingency of the situation in focus (Oyama, 2001a).

Can DST provide a theoretical basis for the self-organization of the organism? Weber and Depew (2001) state that they agree with Griffiths and Gray (1997), who are proponents of DST, about the organism's self-organized characteristic as a consequence not only of genes, but also behavioural, social, and environmental factors of inheritance. Nevertheless, they argue that more emphasis is needed on the bottom-up characteristic of this self-organization. The organism is formed by the autocatalytic closure of the replicating molecules, and the dissipative, self-organized nature of biological processes is a fundamental physico-chemical condition. In a similar vein to Newman & Comper (1990), they point out that genes are not packed with information in the semantic sense, but stabilize the organism's development, enabling inheritance and natural selection (Weber & Depew, 2001, p. 245). From this viewpoint, DST seems consistent with the general ideas of self-organization.

On the other hand, DST has been criticized for its holistic approach (Godfrey-Smith, 2001; Lewontin, 2003; Lamm, 2014). A main problem is that the concomitance of myriad internal and external causal factors of development does not answer the question of why the organism is a focus of development. The organism's life cycle depends on the self-maintenance of its form, and even though it is true that multiple co-existing developmental cycles co-exist, this does not solve the question of how self-organization occurs at the level of the organism. As a reply to this criticism, Oyama (2001b) claims that DST analyses an interaction within the context of the system by considering the interdependency and “reciprocal contingency” of causal relations (p. 182). According to this, the organism and its environment are interpenetrated, hence the dichotomy of the internal and external is called into question. This reply is not sufficient to save DST from the criticism of its holism, which offers a macro-reductionist attitude against the micro-reductionism of the gene-centric explanation. The underlying reason is DST’s attitude of blurring the distinction between the organism and its environment. In contrast with DST, regulative self-organization involves considering the organism as a nexus of numerous causal factors within biological complexity. As I explain below, this is due to the internal relationality that is essential for the individuality of the organism.

Thus far, I discussed DST due to its opposition to gene-centrism. Now I will attempt to clarify the issues with contingency and organicism by making another comparative analysis, which involves DST versus structuralism. As contextualized in DST, contingency appears as an anti-thesis of the structuralist approach. The approach of DST is unable to unify the features of contingency and formal stability, since the emphasis on historicity and contingency appears by antagonizing the structuralist claim that there are laws of form. However, only extreme interpretations of these two approaches, in the former, appraising contingency by ignoring relational necessity, and in the latter, focusing on the “design” characteristics of the organism as if “the design nature” can be stripped from its historical contingency, makes the reconciliation impossible. This does not mean that an emphasis either on contingency or relationality (organizational constraints) per se is wrong, but my criticism targets extreme accounts on either side that exaggerate the role of one of these features in isolation from the other and thus departs from the dialectical unity of contingency and relationality.

Even though the reciprocal contingency of several developmental cycles is the case in ecosystems, emphasizing this fact alone is not sufficient to clarify the core ideas of self-organization. There are two reasons for my criticism. First, contingency is only one aspect of the emergent form, yet relational necessities are as crucial as contingency. Second, self-organization cannot be explained due to a contingent coupling between the internal and the external. Instead, it depends on the internalization of contingency, which makes the organism relatively free from dependence on external conditions. Below, I will clarify the first idea, whereas the second idea will be discussed in the last main section of this chapter.

As explained in the previous sections, contingency is related to the historicity of biological systems in which several causal factors coming together in a random way determine the direction of development. The historical and contingent nature of the biological form is pointed out in DST (Bateson et al., 2001) as well as in the evolutionary contingency thesis (Beatty, 2006). Intertwined life cycles of cellular reproduction, organism, ecological dynamics, etc. constitute intertwined fluctuations in a way that makes these systems open to novel ways of organization. Thus, form should be understood in the context of temporal stabilities of material individuation through this global flow within ecosystems. In this sense, the emphasis on historicity and contingency within DST is correct. The requirements within the relationship between the organism and its environment cannot be represented by any idealized form, and thus not only internal constraints, but also external factor of the selection pressure cannot determine the form per se. On the other hand, biological form is also a consistent unity of parts as a consequence of relational necessities that negatively determine the whole. For this reason, internal constraints must be considered in relation to the capacity for autonomy that is specific to organisms. Structuralism helps to overcome possible deficiencies that can appear when the form is analysed by only due to a contingent coupling between the organism and environment, or to a contingent concatenation of multiple causal factors. Thus, a synthesis of ontogenetic contingency that is represented by DST and relational necessity that is represented by structuralism is essential to understand how the biological form is embodied through the lifespan of the organism. Relational necessities are fundamental, whereas they cannot be thought of as distinct from the incorporation of contingency that is the basis of phenotypic plasticity and homeostasis.

In summary, the main problem is that neither the micro-reductionism of genetic determinism, nor the macro-reductionism of DST provides a final answer to the problem of how the organism's form is dynamically sustained. A crucial aspect that requires explanation is that the organism is a cause by itself, beyond a mechanistic unification of the internal and the external (Lewontin, 2003). The form is gained and preserved in its self-organized condition, and the activity of the organism is basically the sum of responses to keep the form intact. As Lewontin (2001) emphasized, genes cannot organize anything, as they are not active components by themselves. Contrary to the gene-centric view, new approaches in biology such as DST emphasize the role of other cellular and intracellular elements that collectively determine the organization. In principle, this kind of emphasis is necessary. On the other hand, the question then becomes, how does a stable genetic sequence become an instruction for a dynamic and differentiated whole? The answer can be found in the organizational capacity of the whole. The organism's organizational potential allows it to internalize contingency, thereby making the accidental factors essential to its organization.

In Section 2 in general, I have addressed the reflections of hylomorphism for understanding the organism's form as well as interpretations of the formal cause. I have discussed how some of these interpretations deviate from the original concerns in Aristotle's philosophy. I have also discussed the emphasis on contingency in DST as opposed to the alternatives of genetic reductionism and structuralism. Section 2 can be read as the expression of a critical stance that has endeavoured to navigate and clarify the tension between the complementary notions of necessity and contingency. This has mostly focused on abstract principles concerning biological organization, whereas the alternative of regulative self-organization has not yet been discussed. In the remaining part of this chapter, I will deal with this issue, in particular, by delving into the role of temporality. As I have already mentioned, the implication of temporality in the abovementioned approaches to form is a controversial aspect of the problem, as this is seen in Pattee's criticism of Rosen for developing a timeless relational concept of the organism (Pattee, 2007, p. 2274). To deal with this type of deficiency, it is necessary to understand how relationality is realized.

3. Temporality of Self-organization

In the following sections, I return to the question of what makes biological self-organization unique. Some of the main themes of systems biology are “the emphasis on distributed causality, the emergence of form on various scales, the causal interdependencies, and the lack of absolute distinctions between causes and effects” (Oyama, 2001b, p. 184). These identify the aspects of biological causation that are necessary for understanding the regulatory nature of self-organization. Yet, these aspects of causal relations are also present in non-living self-organization. Hence, these causal features point to a necessary, but not a sufficient condition of biological self-organization.

Unlike non-living forms of organization, organisms have a specific internal condition, which is a continuous potential for change. The cases of non-living self-organization due to far-from-equilibrium conditions such as the Belousov-Zhabotinsky reactions, Bénard cells, and flames are limited to the event, whereas biological systems are characterized by a capacity of reorganization, a high degree of functional integration, and combinatory potential. These conditions are specific to the organism’s organization, and they provide a basis for the emergence of ontogeny as a history-dependent process (Salthe, 1989). On the other hand, I stated in the first chapter that the transitional dynamics that directly appear in certain non-living systems are also present within the organism in a more complex way. Now, I explain the ways that these emergent dynamics are involved in the regulative system of the organism that determines the conditions of individuation. Firstly, a critique of the mechanistic approach is necessary, as a demarcation of the internal conditions of a system is not possible within this perspective. After this critique, a non-mechanistic description of the organism’s organization is associated with its potentiality. Through the part-whole relations of the organism, relations determine the identity of the components involved. This also underlies the organism’s high capacity to keep a certain developmental stability condition in the face of perturbations. Finally, a re-evaluation of the philosophical question of emergence is undertaken. As a reply to the criticism based on the synchronic character of the part-whole relationship (Kim, 1999), it is suggested that synchronicity in fact denotes a limit to a temporalized conception of a whole.

Moreover, as an epilogue, biological oscillation is discussed as an example of incorporating nonlinear dynamics. This demonstrates how nonlinear dynamics are incorporated within regulation.

3.1 The critique of the mechanistic approach

A critique of the mechanistic approach is necessary before discussing how temporality is involved in the organism's self-organization. This critique calls into question the Newtonian way of modelling that has been historically developed to analyse non-living systems. The Newtonian basis of modern science, its inappropriateness for biology in particular, has been a topic of discussion since Kant. Theoreticians such as Robert Rosen, Howard H. Pattee, René Thom, Brian Goodwin, and Ilya Prigogine have made similar remarks on the necessity of questioning the established approaches to causality, usually pointing to the inadequacy of the Newtonian approach, and sometimes in search of possible alternatives such as neo-Aristotelian attitudes (e.g. Casti et al., 1989).

Preferences among models reflect our expectations, insights, and sometimes hypotheses on the nature of things. On the other hand, once a model is applied, the results are restrained by a limited practice in line with the ad hoc problems of the relevant model. Thus, it is important to recognize how the empirical results of any model are theory-laden. Although the Newtonian way of modelling was developed in relation to physics, a hidden implication involves that it can be universally applied – usually due to a reductionist approach. This reveals why this issue is relevant in the context of biology. The Newtonian understanding of causal relations has influenced biological research via mechanistic explanation. This is problematic for biology, all other potential problems aside, due to the questionable basis of causation in this worldview. Moreover, this constitutes an obstacle to understanding biological self-organization.[51] In fact, mechanistic explanation is a vague notion with different ways of defining the main issues. The origin of this philosophical account is Cartesian philosophy, which considers the motion of inert

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[51] Mechanisms in biology might be perceived in different contexts: actual causal interactions as opposed to statistic correlations, machine-like conception, mechanicism as opposed to vitalism, or deterministic modelling of systems. The target of my critique here is limited to the Newtonian basis of causal explanation.

physical objects as distinct from mind and purposeful activities. One of the main ideas of the Cartesian philosophy is the machine metaphor for organisms, which has been criticized due to the applications in first order cybernetics (Simondon, 2011) and more recent approaches (Nicholson, 2014). On the other hand, not all types of mechanistic explanations appeal to this metaphor. A new philosophical approach has emerged during the post-positivistic area which considered mechanistic explanation as opposed to functional explanation (Craver & Tabery, 2017). This approach discussed issues such as the underlying mechanisms of the behaviour of a complex system, subsystems of a causal structure, and levels of organization. A main idea in this approach is that mechanisms are decomposable elements that can be localized within the organism. However, this leads to different philosophical problems, namely: decomposability requires prioritizing specific functions (Craver, 2007), not all the mechanisms can be localized, nonlinearity of causal interactions requires different considerations (Bechtel & Richardson, 2010), etc. Considering organisms as nearly decomposable systems involves the idea of modularity, which is a question that is closely connected with self-organization. I will address the criticism of this concept in the next section, but now I will examine more general problems of the mechanistic approach.

There might be certain explanatory benefits within the modern discussion of mechanisms in biology due to notions such as modularity, while the problems with mechanistic explanation as a general scientific approach will be discussed specifically in relation to self-organization. The problem is essentially due to endorsing certain claims about causation that reflect a certain attitude in physics, such as the externality of causes, inertness of non-living matter, and uniqueness of efficient causation. Such claims limit the role of biological research to merely revealing specific configurations of matter. Can mechanistic explanation be exempt from these inherent questions related to causation? I think the answer is negative, since there is no neutral ground in terms of understanding the physicality of a system. In so far as there are postulates such as the atomistic components of a whole, the explanation would be under the influence of theoretical positions that are necessary to justify these claims. As I will try to show below, this brings several drawbacks with it.

Cartesian philosophy and Newtonian physics are regarded as two intellectual sources of the mechanistic approach. However, only the former proposes that matter is inert, whereas the latter has been associated with self-organized characteristics of the systems. With Newton's discovery of gravitational force, it was understood that matter can exert forces beyond direct collision, which inspired epigenesists to find similar forces in biology (Farley, 1977; Moss, 2003; Roe, 2003).[52] This indicates that mechanistic explanation is not necessarily in opposition with ideas regarding a general theory of self-organization. On the other hand, negative sides in terms of the applicability to a contemporary account of the organism's self-organization are overwhelming, as the Newtonian understanding of causality has more fundamental problems. This approach considers only the efficient causes of systems with atomic components in which the internal change of a system can induce a sudden change beyond the system (action at a distance). All of the assumptions implicit here have been either refuted or called into question in later scientific developments. Efficient causes apply to laws of motion, yet it is now quite questionable that other types of causation can be invalidated. Field theory in electromagnetism offers a notion of law that is temporally symmetrical, and gravitational field theory has developed the notion of deformation of the space-time geometry, hence this has required interpretation of fields in relation to potentiality and formal cause (Harré & Madden, 1973), which are not compatible with efficient causation. Atomism is still relevant in today's physics, but obviously the theory has been constantly revised since the seventeenth century when atoms were merely considered as particles with stable extension, and the philosophical implications such as essentialism remain controversial today. Finally, the instantaneous effect of a change in a system, which implies the idea of action at a distance, is refuted in today's science due to the maximum speed limit of any particle in the universe, which corresponds to the speed of light in vacuum. A detailed discussion of these ideas is beyond the scope of this work, but these brief comments are given only to point out the controversial basis of mechanistic conception.

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[52] See the first chapter for Lee Smolin's ideas on the relation between gravity and self-organization.

In the Newtonian worldview, time and space are considered absolute properties of the world, which enables an exhaustive mechanistic analysis of a system's transformation from the viewpoint of an external observer. On the other hand, this absolute notion is questioned by relativity theory, which suggests that time and space are relational categories. This means that there is no privileged observer that represents a universal reference system for measuring time, but instead time is affected by the distribution of matter, and the dynamics of material systems are interactions within space-time geometry. Jaeger, Irons, and Monk (2008) hypothesize that the relativity principle can be applied to positional information in biology. They point out that positional information, which refers to the cells' responsiveness depending on their position in the developmental field, cannot explain how the cells scale their size in proportion to the average size of the tissue and the ability of tolerating perturbations (Jaeger et al., 2008, p. 3175). According to the initial theory of positional information, it is supposed that there is a feed-forward process in which the role of cells is restricted to interpreting this information: As the morphogen spreads from a local source, the differentiation of cells depends on specific ways of responding to linearly decreasing morphogen gradient (by activating specific target genes) due to thresholds through the gradient (Wolpert, 1968). Although the notion has "proven invaluable for guiding experimental research on pattern formation in developing fields" (Jaeger et al., 2008, p. 3176; also see Chapter 3), and later nonlinear degradation of morphogens have been introduced to revise the theory, this was not sufficient to explain the underlying dynamics of differentiation. In contrast to the initial idea that morphogen gradient determines the cell response, but is unaffected by it, it is found in recent studies that regulatory feedbacks play a critical role in the developmental process in several ways, e.g. cellular responses affect the morphogen gradient, signalling activities lead to desensitisation of cell receptors, interaction between target genes restrict the other genes' activities, or signalling of the morphogens lead to cellular proliferation (Jaeger et al., 2008, pp. 3177-3179). Jaeger et al. (2008) points out that the classical understanding of positional information presupposes a unidirectional causation from the field to the cells, and this is in line with Newtonian mechanics, "where the relative positions of bodies are determined with reference to the static geometry of space that is itself unaffected by any objects or processes that are referred to it" (p. 3179). In classical mechanics, the geometry of space in which objects are located is flat, inert, and unaffected by mass, whereas according to general relativity, there is a dynamic space-time metric that is influenced by mass. In a similar way to the logic of general relativity, there is a dynamic interaction between tissue geometry and cellular activity due to feedback regulation at different layers, e.g. morphogens lead to the proliferation of cells, which alters the size of the tissue, and this in turn affects the cellular specification. Jaeger et al. (2008) claim that this reflects a parallelism with the feedback between space-time geometry and mass-energy distribution in the general theory of relativity. On this basis, they propose to extend the theory of positional specification by including the dynamic state of the developmental field according to which the processual nature of biological space-time is taken into account.[53]

This proposal for a revised perspective by Jaeger et al. (2008) also has remarkable implications for the epistemological aspect of mechanistic explanation and its critics. The classical understanding of positional information in Wolpert's model is developed to respond to a lack of mechanistic understanding of the underlying reasons (Wolpert, 1968, 1969). However, a problem in Wolpert's term is the difficulty of establishing a common ground between the development of the cell and the organism. As Goodwin (1987) points out, "the fertilized egg is both a cell and a developing organism" and "it is an organism insofar as it is totality describable by a field; it is a cell insofar as it embodies the specific constraints" (p. 176). He goes on to claim that acknowledging the organism as a self-organizing field solves this problem (Goodwin, 1987, p. 177). In this sense, Goodwin's self-organization theory puts forward a structuralist account against the gene-mechanistic explanatory project (Winther, 2011, p. 415). As a consequence, Goodwin and Cohen (1969) suggest a revision of Wolpert's model, stating that positional information presumes that every cell has access to a clock and can read a map, whereas according to their model, "the map arises from wave-like propagation of activity from localized clocks or pacemakers", as the "individual cells

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[53] The authors also remark some challenges in this comparison: General laws are relevant for the theory of relativity, whereas laws are thought to be non-existent for biological processes. Also, mass-energy is conserved in the physical model, whereas biological systems are thermodynamically open (Jaeger et al., 2008, pp. 3180-3181).

are supposed temporally organized" (p. 49). Along the main lines of mechanistic explanation and its critique in favour of self-organization, it is possible to see both the traces of a criticism of the gene-mechanical explanation and a tension between efficient causes in the former and a temporal understanding of form in the latter. The abovementioned view by Jaeger et al. (2008) puts forward an alternative that focuses on the interactivity of form and matter due to the implications of temporality, and contributes to the criticism of Newtonian mechanicism on the same lines as Goodwin (see Section 3.3 for Goodwin's general approach). Rosen's theory on anticipatory systems depends on a similar interactivity between information and time, as it claims that biological organization depends on how time is internalized within the organism and passed between generations (Rosen & Kineman, 2005, p. 407).

Despite the unjustifiable basis, the standard mechanistic modelling approach that reduces causation to attaining velocity vectors to points in a phase space continues to shape our worldview, thereby permeating into scientific and philosophical discussions. As pointed out by the proponents of self-organization in different areas, e.g. Prigogine & Stengers, (1984/2017), Kauffman (2000), and Smolin (2013), whose ideas were briefly explained in the first chapter, a high intellectual cost of this limitation is the neglect of the implications of temporality in complex systems. Due to the analysis of trajectories as closed and deterministic systems depending on initial conditions and the laws of nature, temporality is reduced to a logical implication because it is presumed that the outputs of a closed deterministic system are already given by the inputs (Smolin, 2013). As to the closedness of a system, a major problem in a mechanistic approach that creates a drawback for understanding self-organization is the lack of objective criteria for making a distinction between internal and external conditions. Organisms are open thermodynamic systems, which means that there is exchange of energy and material between the system and its environment. However, it is also true that "organisms are open systems that handle flows of matter and energy by means of and for the maintenance of their metabolism" (Soto et al., 2016, p. 79), which makes organisms relatively independent from external conditions. This partial independence from external conditions co-exists with the openness of the system, which requires an analysis of the dynamic basis of internality. Mechanistic analysis is not capable of explaining the physical basis of this specific condition because this type of modelling cannot offer any objective criterion as to the boundaries of a closed system. In this type of analysis, a certain number of degrees of freedom are considered within isolated conditions, and the rest of the world is ignored. There is no way to establish the objective difference between internal and external conditions of an interaction, and there cannot be any intertwined levels of organization other than composition. According to this one-dimensional approach, different mechanisms correspond to different parts of composition within a complex system, but the change of the system that is constituted by these mechanisms is to be analysed as a single trajectory. Therefore, mechanistic approaches cannot offer an explanation in terms of the dynamics of individuation other than the continuous co-existence of internal and external conditions.

Restricting self-organization to an approach that only considers internal dynamics cannot be an alternative to this one-dimensionality, either. Instead, the objective criterion of individuation is necessary to understand how external contingency is internalized. Externally, the organism interacts with its environment as a whole, but internally, the whole is the mediator of causation at multiple levels, whose functional integration is enabled by feedback regulations. As a consequence of this, a self-organized organism is a system in which the degrees of sensitivity of the parts towards each other change over time, since internal elements can be induced by each other. The objection to the mechanistic approach through the abovementioned lines does not depend on an actual state of the internal, such as the membrane closure that marks the internal unconditionally. On the contrary, it refers to a claim that the internal state of a system is not simply a matter of composition, but temporal characteristics of organization determine what is internal in the context-dependent situation. Due to this dynamism, the boundary of individuality is conditional, defined due to the processes involved, and intertwined internalities appear throughout the sub-systems of the organism. If this crucial element of interactivity between material processes and the geometric basis of organization is ignored, then the analysis of self-organization would not be able to overcome the limitations of the mechanistic approach which were previously discussed. Thereby, organisms would be considered as the natural extension of their environment, simply a deterministic correlative to the ecosystem, without any acknowledgment of their causal agency.

3.2 Potentiality of the organization

In the previous section, I criticized the mechanistic approach due to its questionable basis of causation in general, and for not having a sound basis to make a distinction between the internal and the external. An essential condition of internality and individuality in a living system is a certain degree of causal insensitivity to perturbations. Causal insensitivity does not mean that the system in question is causally detached from the external, but it shows that a one-dimensional causal connectedness is not representative of actual biological processes. This condition is also the basis of organizational robustness. In this section, I will argue that robustness is due to the potentiality of biological systems, and potentiality is a distinguishing aspect of regulative self-organization. Specifically, I claim that degeneracy within biological systems is indicative of causal potentials. The studies on potentiality in living systems can be traced back to Hans Driesch (see below), whereas the relevant philosophical implications have not been sufficiently discussed. The discussion of potentiality is a continuation of the criticism of the mechanistic approach in so far as this approach reduces causal relations to the actual states of systems.

Biological systems cannot be understood as unitary causal pathways because they consist of causal networks in which alternative forms of interconnectivity appear as functionally equivalent. This is known as the degeneracy of biological systems, but I suggest that degeneracy should be considered as part of the potentiality of biological interactions. Degeneracy refers to “the ability of elements that are structurally different to perform the same function or yield the same output” (Edelman & Gally, 2001, p. 13763). It is the “capacity to produce the same result by different strategies, in contrast to a redundant system in which the same result is produced by the same strategy” (Greenspan, 2001, p. 385). As it appears due to the alternative forms of interdependency within living systems, degeneracy calls into question the neat separation of causal contributions. Degeneracy is a main source of gene flexibility, but it is also relevant to other biological functions such as the immune system and the nervous system (Edelman & Gally, 2001; Greenspan, 2001).

Mitchell (2008) discusses degeneracy with respect to questioning the modularity of biological systems. Modularity denotes the degree of separability or variability of a subset of a system without leading to any change in the functional relations within other parts. In biological systems, a modular unit refers to structures that are internally stable and partially independent from other parts. Specifically, Mitchell (2008) questions Woodward's (2005) formulation of modularity as a type of causal invariance, that is, a causal relationship within a system that does not intervene with other causal relations when it is changed. Along with invariance and insensitivity (see Woodward, 1997; Woodward, 2006), modularity forms the basis of Woodward's interventionist account of causation. In a causal relationship that is defined according to interventions, a change in the variable *Y* occurs due to a change in the value of *X,* and this relation remains invariant in different contexts. This implies that only a specific sort of change that occurs as an intervention in *X* is reflected as an effect in *Y* (Woodward, 2005, p. 94). As will be shown below, Mitchell's (2008) account is also critical of modularity.

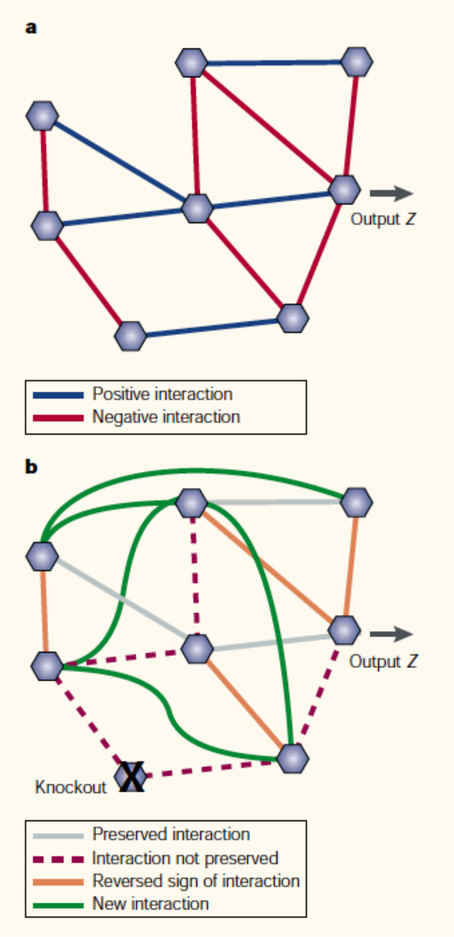

Figure 4.1 The knockout experiment. Represents the re-organization of the network (from Greenspan, 2001, also cited in Mitchell, 2008).

The example that Mitchell (2008) puts forward is concerned with genome flexibility. According to the idea of modularity, if the intervention (in the case below, knocking out the gene) does not lead to a change in the causal network, then it is considered as causally detached from the network. However, certain cases of knockout experiments show that this might not be the case. The general technique in knockout experiments involves the removal of a specific gene sequence, usually from a mouse genome, so that scientists can make a controlled experiment focusing on the causal contribution of the gene that has been knocked out. In most of the knockout experiments, the subsequent lack of the gene either results in phenotypic differences or non-viable organisms. Whereas in some cases, when a specific gene is removed, the genetic network recovers its function by making new connections among the other genes (Mitchell, 2008, p. 700; see *Figure 4.1*). Therefore, this example shows that there might be cases which prima facie meet the criterion of modularity, since a change in the subset of a system does not lead to a perturbation in the rest of the network, whereas the underlying causal pattern is different. This is a case of degeneracy in the genome, as the gene that has been knocked out was not redundant, but a functional part of the regulatory network. In the new situation, the network recovers its function by reorganization, thereby maintaining the phenotypic function. This demonstrates that some marginal cases exhibit a conflict in terms of Woodward's (2005) interventionist causality.[54] Functionally equivalent cases prove that causal interventions should be reconsidered in the light of feedback loops and complex network dynamics. This shows that the causal sensitivity of the internal networks is context-dependent. In certain cases, "a starting mutation sensitizes the system for further genetic perturbations", and other mutations can be activated by a sensitized background (Greenspan, 2001, p. 384).

Degeneracy is actually a concept that denotes a common characteristic of living systems which are highly relational, metastable, and hierarchical. It follows that the causal role of the part is determined by its interrelations. Through the

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[54] In fact, I believe that this example does not necessarily call into question modularity, albeit hinting at the complexity of the problem. The example given concerns Woodward's (2005) interventionist notion by showing that some of the cases appearing as modularity formally might not be so, yet it is not proving that any case of modularity would be inconsistent. Moreover, the actual case of modularity concerns the degree of decomposability, which points out an asymmetry in the interconnectivity of a system. Certain modules at different levels, such as gene sequences, or subcellular structures, are evolutionarily preserved, and higher functionalities have appeared by reshuffling these units (Moss, 2001; Schlosser & Wagner, 2004). In this regard, I believe that the original concept in biology might be useful to understand the causal implications of the difference between the internal and the external. It is also discussed in relation to the contingency and self-organized regulation of the organism (Moss, 2001).

levels of organization, the complex nature of interrelations creates a combinatory potential, whereby different combinations of causal networks can be functional and some of these alternatives can be functionally equivalent. Degeneracy is effective at different levels from genotype to phenotype. At the genetic level, 64 different combinations of nucleotide triplets code for 23 amino acids (Maleszka, Mason, & Barron, 2013). For instance, although albumin is a functional protein that is not redundant, it is found out that some healthy human individuals lack this protein. This shows that certain adjustments have tolerated the lack of protein (Edelman & Gally, 2001), and "the RNA polymerase holoenzyme that catalyzes RNA synthesis itself appears not to be a single, well defined entity but, rather, is a degenerate population of complexes with different polypeptide chain compositions" (Edelman & Gally, 2001, p. 13764). Several other cases of degeneracy have been discovered at different levels of organization from the genetic level to body movements. Organisms can utilize degeneracy. In bacteria, environmental settings stimulate the genetic code with degeneracy into forming robust networks, thereby producing adaptive results such as increased rate of protein synthesis (Maleszka et al., 2013).

This combinatory potential of the interconnectivity of parts proves the common phenomenon that various strategies can be used to perform the same function, and therefore a specific part that seems as redundant might be involved in an alternative type of functionality that is latent in the actual system. Functionally equivalent causal pathways can be found in cellular differentiation, epigenetic regulation, or metabolic activities, and they show the potentiality of organization in biological systems. This also indicates that it is not the parts by themselves, but the ways that parts are interrelated through developmental and epigenetic processes that determines the organism as a whole. The regulatory nature of epigenetic integration provides a high level of flexibility that is required for the coordinated and context-dependent expression of multitudes of genes (Maleszka et al., 2013, p. 194). Therefore, the organism constitutes a potential of different network interactions, which cannot be reduced to an actual state of the organization. Although this aspect of organisms has been revealed since quite early studies in biology, it is underemphasized because phenomena such as degeneracy are sometimes overlooked due to the reductionist bias in scientific theories (Maleszka et al., 2013).

Degeneracy refers to a many-to-one relation between the components and the function, whereas the complementary notion of degeneracy is pluripotentiality, in which one component can be used in different functions (Maleszka et al., 2013). Historically, pluripotentiality has been put forward as opposed to preformationism. The issue has been contested in a classic controversy between Wilhelm Roux and Hans Driesch in the nineteenth century.[55] In his experiments with frog blastomere (the embryo cells at the early stage), Roux took out one cell and observed that the remaining cells developed into a deficient embryo. This led Roux to conclude that cellular differentiation is mechanically predetermined, agreeing with Weismann's germ theory that some essential parts within the cells fully control the development. On the other hand, Driesch found out the opposite. According to him, each blastomere had the capacity to develop into a full embryo, and it is the whole organization that determined the development of each cell. Today, the latter view is vindicated (Bechtel & Richardson, 2010). Preformationism is refuted, since it has been shown that the development of the embryo is not an exact unfolding process. Instead, the cells at the beginning phase are pluripotent, meaning that they all have the capacity to differentiate into any part of the body. Later developments in stem cell research is based on the pluripotential capacity of cells, as it has been found out that cells can differentiate or return to the initial undifferentiated state. This shows that the components of the developmental process have the potential to be utilized in different pathways, which is a potential that is realized by the induction from other cells as a consequence of interrelations. In fact, interrelations dominate the development of parts through the self-driven process, as the parts' identity is determined within the processual context.

Pluripotentiality is not limited to stem cells. It has been shown that neural cells keep their developmental plasticity throughout their lifespan. This means that cells can be recruited in alternative functional networks, which can also be used to

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[55] Driesch mentioned the self-regulation of the organism's development, and used the concept of field in embryology for the first time. In this sense, he has been considered as one of the pioneers of self-organization (Goodwin, 1987).

regain a certain function after damage to the system. This interactive complexity between degeneracy and pluripotentiality is likened to a bowtie, in which “many inputs funnel into a thin knot of interlocking networks and subsequently many corresponding outputs fan out” (Maleszka et al., 2013). Components of the living system can be utilized in different ways, which implies the emergence of a combinatory potential. The possibilities of the organizational bowtie converge at a certain layer, as the networks also appear as structural constraints, and then re-expands because the number of alternative viable forms increases once interconnectivity is established. All these examples show that biological function is not sensitively dependent upon a specific configuration of components. On the contrary, regulatory networks have the capacity to re-stabilize themselves, or invent novel forms of organization in a dynamic way.

How should we interpret this in terms of self-organization? At this point, I will return to the problem of emergence in part-whole relations and the criticism of the mechanistic approach. As mentioned in the first section, Kim suggests that functionalizing the inputs and outputs of a system reveals the epiphenomenal nature of emergence. Depending on the potentiality of living systems, Kim’s critique of emergence can be challenged. What Kim’s (1999) analysis in fact suggests is to reduce the emergent system to a mechanistic understanding of a dynamic system. However, the capacity for reorganization is an emergent property due to the potentiality of the system, which is why the causal model of physics that concerns a single causal trajectory is inadequate. The biological system is not a causal pathway that can be reduced to a single process, but a distributed network that has alternative capacities of interconnectivity, in which the causal role of the parts is context-sensitive (Greenspan, 2001, p. 384). Thus, the high interactivity of biological systems calls into question the idea that a subset of a system can be causally analyzed in isolation, which is borrowed from Newtonian physics. The mechanistic approach in biology does not provide a sufficient explanatory basis in the face of the potentiality of biological systems.

One could still argue that the potentiality of biological systems does not rule out the idea of mechanical predetermination, since physical transformation of a system is sensitively dependent on the initial conditions. This potentiality is also dependent on the functional equivalence of alternative developmental pathways, that is, multiple realizability of the function. None of these features exclude the possibility of mechanical predetermination in principle. A discussion of this would concern the interpretation of potentiality in physics, and I will not develop such an argument, since I have already discussed some general problems with causation in the previous section. Recall, I offered a critical analysis of the mechanistic worldview on the basis of its negative implications for theories of biological processes.

Let us consider the mapping between genotype and phenotype. Can we assume that in the causal process of the organism's life cycle, the phenotype at t_n is the function of the genotype at t_{n-1}? Sure enough, the phenotype is an output in so far as it is a result of the interaction between the genotype and environmental conditions. Even though different theoretical approaches emphasize either the role of genes, or the role of environmental factors, there is a consensus that the genotype provides the norm reaction. In other words, the genotype provides the developmental source of traits differing depending on the environmental influence. Based on this, the proponent of mechanistic determination could insist that if one could specify all the genetic and environmental inputs, then it would be possible to predict the deterministic output in the phenotype. However, even if this were possible, it would hardly give an idea concerning the potentiality aspect of biological systems that emerges due to relationality. Mechanical determinism reflects certain expectations, and in this case, potentiality is not included in the mindset of this specific way of modeling causal relations because it is not a concept that is evident in the actual condition of efficient causes.

The potentiality of organization is the underlying reason for robustness in living systems. The overwhelming role of relational networks enables the organism to reconfigure its internal conditions. In this section, I have addressed the ways in which potentiality characterizes regulative self-organization and why it is contradictory to the mechanistic explanation of regulation. Although this is also indicative of the emergent nature of biological processes, the content of this section was not directly related to diachronic emergence or the temporality of form. Rather, this section considered degeneracy as a capacity that manifests a fundamental property of causal relations, namely, potentiality. In the following section, I will consider the emergent nature of biological processes as the final element of my argument on self-organization.

3.3 Synchronic and diachronic conditions of self-organization

In the previous sections, I explained how relationality determines form, and how many-to-many relations that create multiplicity between structure and function lead to an expansion of the possibility space of organization, making the organization more robust. This also enables the discovery of novel functions in evolution due to the combinatory potential of lower-level elements. I think self-organization can be a viable theory in so far as it is developed as a modern system of epigenesis, which involves the incorporation of new organizational possibilities during the ontogenetic process. Regulative self-organization in organisms is capable of constantly maintaining its potential for change which is constituted by a network of processes. This is contrary to a system where its self-organization is solely due to spontaneous factors and limited to a specific process. The underlying reason of this constant potential, which also relates to the question of how the form of the organism extends over time, still needs to be answered. In this section, I will attempt to answer these questions both by considering the previous discussions within this work and by introducing a new claim about the temporality of form. I propose that there are two essential aspects of temporality due to the organism's dynamic form, which are diachronic and synchronic. The diachronic condition refers to the transformative role of relational processes throughout the organism's lifespan. Thus, the diachronic condition is associated with organism's change in time as a self-organizing field. The synchronic condition refers to a limit condition of temporality that is realized through the interplay between internal and external sources of organization, in which the organism can incorporate external novelties. I argue that the way that diachronic and synchronic conditions are coupled enables the organism's constant potential for change. This is an issue of how the recursive, stable, and transitional dynamics are materialized in the organism. In this context, I will discuss the role of biological oscillation that is crucial both for developmental processes and physiological regulation. Oscillation appears both in non-living and living processes, and it is significant as it reveals how transitional self-organization within non-living processes is connected to regulative self-organization within the organism.

Let me begin by addressing the issue through Brian Goodwin's ideas on self-organization. As explained in the previous section, Goodwin rejects the gene-centric explanation and focuses on the role of developmental constraints. In this approach, the constitution of the whole is not a matter of co-existence of decomposable parts, rather it is a matter of generating heterogeneity. The organism is a self-organizing field, which suggests a formalizable structure (Goodwin focuses on the mathematical description of this formality), and thus, a consistent whole from the beginning of the process to the end. This is because the organism's internal relations can remain invariant through the systemic transformation of the whole (Goodwin, 1987). This notion of self-organization primarily focuses on the developmental stability of the embryo, but let us consider applying this notion to the internal stability that persists throughout the whole lifespan of the organism. The organism undergoes several alterations through its lifetime, which are due to both stochastic factors and epigenetic differentiations depending on environmental cues. On the other hand, certain characteristics remain invariant vis-à-vis the variable conditions that are contingent. Sure enough, this condition of the organism depends on being a product of evolution. However, as the mentioned property is a type of plasticity, the emerging phenotypic process of the organism cannot be strictly determined by genes. In other words, the organism's development is open to external contingencies in the sense that it incorporates these factors. For example, in the case of developmental conversion, the organism uses the inputs from the environment to follow alternative genetic programs (Smith-Gill, 1983). The organism's organization is also capable of coping with novel conditions (see Chapter 3).

My emphasis at this point involves the idea that, beyond a specific case of plasticity during a certain stage of development, this loose understanding of plasticity as an interface between changing and unchanging characteristics of the organism is an inherent property of form that is maintained throughout the lifespan. Goodwin begins from the totality of form, both in the spatial and temporal sense, and addresses the lower-level elements such as cells in relation to developmental constraints (see previous section). By applying Goodwin's approach to self-organization to the whole lifespan of the organism, it could be possible to give a four-dimensional account of form that is inclusive of temporality, as the organism is a self-organizing field throughout its lifetime. Therefore, the form extends in time as well as in space. However, if the element of contingency that I emphasized is not considered, then a potential pitfall for the revised approach involves a conceptualization of form as an unfolding of a predetermined process. This is because a lifespan that is isolated from external and internal contingency can only be characterized by a deterministic growth. But on the contrary, contingency exists, which is why the lifespan is not characterized by a deterministic growth, but a relative invariance into which contingency is incorporated. Temporality cannot be reduced to spatial relationality in a pure structuralist approach. This means that relationality cannot be simplified as a mechanistic process of the unfolding of the form in which time is neutralized through deterministic mappings of the developmental trajectories. As emphasized in the critique of the mechanistic approach, historicity and contingency cannot be excluded from the causal explanation depending on relational necessities, which would result in ignoring the real implications of temporality due to the openness of processes.

Goodwin (1987) points out that the organism is the unit of organization and the long-term determination of form is due to the morphogenetic transformation of the whole. On the other hand, the co-existence of contingency and formal stability must be understood in relation to the internal-external relationship. Recall that in Section 2.3, I explained that, instead of a direct coupling between the organism and the environment, contingency is internalized. Through the lifespan, neither the internal relationality nor the internal-external relation can remain invariant. What remains consistent is the organism's constant potential for organization. Internally, we can speak of a causal closure in the sense of causal circularity of the reproduction of parts, which is emphasized by the autonomous perspective (Moreno & Mossio, 2015), whereas the organization of the organism is still an open process, and is maintained by internalizing external contingency. Self-modifying systems are autonomous, but they don't have closure, as they constantly seek new relations with their environment (Salthe, 2001). The organism can never be perfectly pre-adapted to environmental conditions due to the novelty of events. As we have seen in the example of the immune system in the third chapter, the organism must cope with unprecedented events through its lifetime.

A better conceptualization of dynamic form that is extended in time would require considering it as an interface between its internal consistency and external contingency. The form is sustained to the extent that the external contingency is amassed within the form, which is evident from the phenotypic plasticity. For example, brain functions can be altered in order to adapt to new conditions throughout the lifetime, i.e. cells can be associated with new functions, or the location that performs a specific function might change. This high degree of plasticity is also a basis for cognitive abilities such as learning and memory. Furthermore, plasticity can be manifested as the regaining of a specific function by reorganization when there is damage to the system.[56]

The lifespan of the organism is a process of the formation of heterogeneity characterized by the sequential solidification of organizational possibilities at multiple levels. The organism has different degrees of fluidity because it possesses both short-term and long-term mechanisms in order to adapt to changing conditions. This suggests a hierarchy of organization in the spatiotemporal differentiation, and different degrees of interactivity with external conditions. Heterogeneity first appears in embryonic development in which the temporal sequence of the events is directly reflected in the lifetime characteristics of the form due to the segmental differentiation of parts, cellular differentiation of the pluripotent cells, bifurcation events, etc. In this process, genes contribute to the stabilization of form, but they also provide a developmental source that can be utilized in different ways due to mechanisms such as alternative splicing, without being able to create organizational dynamism by themselves. Changes in the phenotype due to epigenetic regulation create a further condition of differentiation. As a relatively synchronic condition of the organism’s dynamic form, metabolic regulation emerges as the most fluid level of change, but this is also where the

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[56] For this reason, it is claimed that the brain in vertebrates (backboned animals) is in a constant process of embryogenesis (Ruyer, 2016).

homeostatic condition is related to the mediation between the internal and the external. All these causal factors at different levels are coupled in self-regulation. For example, cellular regulation occurs due to genetics, epigenetics, and metabolic processes (Roux-Rouquie, 2000), and nonlinear dynamics are utilized in different ways at these levels. Beside the morphogenetic characteristic of the developmental processes, nonlinear processes are also involved in the self-organization of metabolic activities utilizing ATP such as the self-organization of the cytoskeleton (Kirschner, Gerhart, & Mitchison, 2000). The hierarchy in the temporalization of the organization is evident here. Certain fundamental causation patterns, such as positive and negative feedbacks, are general at all these levels, whereas the underlying dynamics of the realization of form are quite different at each level with different paces, and different degrees of fluidity. What I mean by different degrees of fluidity depends on the reversible, relatively reversible, and irreversible aspects that appear while responding to external conditions. For example, a contingent change in temperature might trigger homeostatic responses for thermoregulation in a mammal, whereas it might play a role in determining the sex during the embryonic development of a reptile. These two correspond to distinctive and qualitatively different ways of responding the environment, which have dramatically different consequences for the dynamicity of form.

The abovementioned description is indicative of the temporal nature of organization. This raises the following question: As an open process, how does the organism's form extend in time through its consistent activity of self-regulation, and in particular, how is it possible that contingency and relational necessity are unified within the form? I think the answer lies in epigenesis. Epigenesis is the idea that form is acquired progressively as an adaptive process (Moss, 2003), while it is not pre-existent in the initial state of the organism. The origin of the idea can be traced to Aristotle, whereas the modern context in biology dates back to the eighteenth century, when the controversy between preformationism and epigenesis was a major issue in embryology. The discovery of the pluripotentiality of cells helped to refute preformationism in favour of epigenesis, but as we have seen, other theories of implicit preformationism still survive in genetic reductionism. On the other hand, epigenesis also relates to a metaphysical question beyond development, concerning the emergence of form over time (Maienschein, 2017). This is why, to promote epigenesis against preformationism, it is necessary to discuss it in a broader context. In the context of ontogeny, this additional claim corresponds to showing how the emergent aspect of form is due to the openness of living processes. Otherwise, time-extended form would be reducible to a certain state through the organism's transformation; thereby an implicit idea of predeterminism would be permissible.

The question is whether it is possible to offer an approach that can incorporate both epigenesis and morphogenesis. Without epigenesis, the diachronic condition of morphogenesis would be reduced to a predeterminist unfolding of the form. On the contrary, epigenesis depends on the condition of being unformed at a certain time, but simultaneously including the potential to be formed, which is a synchronic condition. Below, I will explore this idea further.

In the first section, I discussed the argument by Anjum and Mumford (2017) that defends the emergence of downward causality due to the synchronicity of cause-effect relations. I also considered the controversial aspects of this position. My argument concerning the emergent nature of the organism originates from this claim about synchronicity, yet it is slightly different from Anjum and Mumford's position. It is not exactly dependent on the claim that causation is synchronous, which requires a discussion of some problems such as non-locality, but it is based on merging synchronic and diachronic aspects of temporality within the explanation of living systems. I claim that a radical notion of relationality implies that the supposedly atomistic elements are not isolated from their relational and temporal context within the system. In other words, components of a whole cannot be thought of as instantaneous entities that constitute the whole in a merely compositional relation. To explain this, I will return to the ideas developed in the previous chapter. I discussed organizational hierarchy as something different from composition in the sense that the organization is more than an ordinary aggregation of parts. My argument involved a notion of organizational types that are characterized by the bio-generic properties of living systems. The idea I am proposing here is complementary to that claim. Beyond pointing out that living systems necessarily involve organizational hierarchy, I argue that no material aggregation is possible without an association of cross-level dynamics in one way or another. Some of the phenomena might seem merely flat, lowest-level relations between the parts. However, this appearance is misleading, as there is always an underlying relationality that leads to the emergence of organization. This idea depends on the profound conception of relationality that I explained in Section 2.2, where I conveyed the idea that what is known as matter cannot be exempt from context-dependent positioning of parts and a certain degree of organization.

Based on this, I define the synchronic condition as an irreducible limit of diachronicity in which multiple diachronic processes at different levels coincide in a partially unformed, but responsive state. In this sense, it refers to non-directionality of organization at a certain time period, which is why it is not necessarily characterized by a frozen moment, but a relative condition in the face of diachronic change. In every instantiation of stability, or in any short-term temporality, there is an irreducible limit to localizing compositional elements because interrelations are heterogeneously extended in time. Thus, the synchronic condition is a synergetic situation in which relationality, that is, the potential interconnectivities between the components of the system, determines the transformative nature of the causal relations. Within this condition, these interrelations are characterized by partially unformed, thus under-individuated heterogeneity, in which diachronic temporality is not actual, but only a projection. Despite Kim’s (1999) criticism of emergence, this synchronic condition cannot be formulated as an input-output function because the latter requires an atomistic conception of the components where the initial state and the end-state can be distinguished within a trajectory. However, the synchronic condition is based on the claim that there is a limit to the decomposability of a system into sequential moments and atomistic elements, since these atomistic elements cannot be thought of as isolated from their temporality. This objection also relates to a critique of reducing a macro condition to its micro-level elements. In a way of thinking that is limited to composition, the notion of micro-level element always requires a supposed state of instantaneity, a momentary but frozen imagination of the parts, that is stripped from their temporality. However, this also implies isolating compositionality from its causal context.

This claim is based on the idea that a self-organized system has the capability to exploit contingently arising opportunities within the complex asymmetry of its relations. The underlying dynamics of this are the selection and utilization of lower-level dynamics at a higher level (Salthe, 1989; El-Hani & Emmeche, 2000; Emmeche, 2004; Haken, 2013; Longo & Montévil, 2014; Witherington, 2014), which is opposed to the predeterminist notion of biological organization. As an emergent aspect of organization, both the synergy of the interrelations within the system and the condition of metastability in which the synergetic situation can shift the organism into alternative states is emphasized (Simondon, 2009; see Section 3.2). According to this, potentiality for change is latent in a certain state, and novel situations of relationality can appear. In relation to metastability, this dynamism corresponds to coupling the functional requirements emerging in diachronic condition and the organizational solution hidden in the synchronic condition. Therefore, in the case of ontogeny, the synchronic condition is a limit to the minimizing of the temporality of organization which appears as a type of mediation between the internal and the external. In this hierarchical system that involves functional relations, the irreducibility of lower-level potentials indicates a condition of unformedness that becomes a source for multiply realizable states where the diachronic dynamics of individuation can select their own actuality. The centralized networks of organization which enable goal-directed processes to act as downward causes (see Chapter 3) find organizational possibilities within this irreducibly heterogeneous condition of materiality.

These two conditions of temporality are relative to each other. In actuality, the synchronic condition cannot be considered without diachronicity because of the unavoidable aspect of temporality. On the other hand, even though the synchronic condition is irreducible, it appears as a processual stability, mostly depending on the recursive nature of causal interactions in biological systems. This processual nature of synchrony is consistent with the observation that any part-whole relation that appears in a synchronous condition is also dependent on the diachronic condition of the organization. The diachronicity underlying synchronous conditions is highlighted by Nakajima's (2004) assertion that "the transformation identifies the unity of the process based on the identity of pattern, not the identity of individual participants" (p. 518). For example, a cell's synchronic constitution depends on the constant replacement of the constituents with new ones, or a synchronic organism depends on constant multiplication and death of cells. These elements point to the irreducible characteristic of diachronic organization hidden in the instantaneous condition of the biological entity (Nakajima, 2004). It follows that an idealization of synchronicity and diachronicity, which in fact results in a neutralization of these factors, should be rejected. The synchronic condition does not emerge as an ideal, but as a de facto situation that is defined in relation to the diachronic aspect. Here, the ideal condition of diachronicity refers to an extension in time without this minimal condition of heterogeneity at a lower level, and the ideal condition of synchronicity refers to an extension in space without temporality, i.e. a frozen state. The impossibility of the neutralized conditions of diachronicity and synchonicity is due to the inevitable temporality of systems, which means that these two aspects must be co-existent at the basic micro level. Therefore, there is a limit to the reducibility of the spatiotemporal nature of the organism to either atomistic (spatial reductionism) or momentary (temporal reductionism) elements of the system.

According to a similar distinction, the synchronic type of regulation occurs by neutralizing perturbations and keeping the system in a homeostatic condition, whereas the diachronic type appears when parameters of the system reach a limit, thereby a change in the organizational state occurs (Roux-Rouquie, 2000). I think this distinction could potentially be consistent with my account explained above, if it is also conceded that the synchrony is a de facto condition, and that the diachronic type of regulation is defined relatively. This relativity of stability accords with the account of levels of organization that I discussed in the previous chapter. Remember that a higher-level process is perceived as stable because the frequency of change is less (Simon, 1962). If this is understood in relation to the synchronous condition, then it must be concluded that the organism is synchronously stable relative to its ongoing cellular replacement within, whereas it is dynamic relative to the population it belongs to. In addition to this relativity of stability across different levels of organization, the basis of self-organization is that these processes with different frequency rates are coupled with each other. This enables the organism to simultaneously cope with a constantly fluctuating environment and keep its internal condition intact.

De facto condition of synchronicity is due to the relational realization of these two conditions depending on the individuation of the process. Individuation is a byproduct of the hierarchical nature of relational systems, in which the part and the whole are determined in relation to each other due to the nonlinearity of causal relations. In other words, there is no substance in materiality and nothing exists but relationality. Recall that one of the approaches to emergence presupposes that emergence does not have to contradict reduction (Wimsatt, 1997). Here, my argument concerning a “strong” notion of emergence calls into question the parthood that is subject to configurations. If relationality determines what the parts are, and there is a basic level of irreducibility in the spatiotemporal characteristic of relationality, then this means that the argument based only on the synchronic condition between the parts and the whole is incorrect. There is a causal asymmetry between the parts and the whole due to the temporality of the organization. This asymmetry originates from the overwhelming nature of relationality that acts on the individuated parts. Thus, as previously explained, the synchronic condition cannot be understood in any frozen moment. Parts are considered as decomposable elements, but in fact, the idea of an isolated part is a fiction based on abstracting parts in alternative combinations of causal relations.

On this basis of temporality, it is possible to offer an approach of epigenesis concerning the ontogeny of the organism. Novelty in ontogeny can co-exist with the relative invariance of the diachronic condition. This is because either by reorganization, by a transition of cellular determination from an unformed state (Newman & Forgacs, 2005), or through physiological changes, new possibilities that are organizationally robust can be discovered. Moreover, biological organization can respond to uncertainty in different ways, which creates an expansion of possibilities.

I have already established that the organism’s form is extended in time. In contrast to non-living entities, an organism’s form at a certain stage is highly correlated with the temporality of organization throughout its whole lifespan. Now, let me explain how this condition of synchronicity is realized in the organism, and how it relates to the question of regulative self-organization. I have argued that an ideal condition of synchronicity is not possible, but also that the synchronic condition in biological systems emerges based on the recursive nature of internal processes of the organism. De facto synchronicity is due to the constant re-production of the self, which is reinforced by the directional nature of organization, that is, the capacity to adopt different states. This dual condition is the underlying reason why a synchronic condition uniquely creates a potential for internal transformation by enabling new pathways for the self-maintenance of form in organisms.

The basis of this is the role of negative and positive feedback loops within the body, which are usually coupled with each other. The importance of positive feedback is evident in the formation of autocatalytic reactions, which requires their own products to accelerate themselves. On the other hand, negative feedback is essential for processes of oscillation. These feedback relations are evident at various biological levels including metabolic processes, cellular differentiation, and the regulation of gene transcription (Roux-Rouquie, 2000). In this sense, biological oscillation has a special role in terms of coupling different rhythms of change within the system. Oscillation is a pattern that unifies recursive and history-dependent dynamics of change at different levels, performing different functions. Biological oscillators that are internal to the organism have a fundamental role in regulative self-organization, as they become the temporal anchors of more fluid processes that are built upon a developmental basis. This is because biological rhythms are relatively robust symmetries, and “the organism is tuned to (and expects) their iteration” (Longo & Montévil, 2014, p. 102). Moreover, the sources of rhythmicity that are endogenous to the organism are synchronized with each other – and in many cases, rhythms are dependent on external sources such as the diurnal motion of the Earth.

In previous chapters, I defined the transitional type of self-organization merely based on nonlinear elements from the organism’s self-organization, but also highlighted that nonlinearity is incorporated in regulative self-organization. In this chapter, I objected to an idealized understanding of synchronic condition by arguing that it involves a limit condition due to the processual nature of things. Now, I would like to focus on how these two conditions, namely, nonlinear dynamics and temporality of form are realized in living systems. Thus, I will examine some examples of oscillations in the organism's self-organization. These examples also help to explain how diachronic and synchronic conditions are coupled, as different rates of rhythmicity as well as recursive and history-dependent interactions are interrelated through a network of endogenous oscillators. As a consequence, dynamic form is dependent on the unification of fluctuations with different frequencies. Since oscillation is a common pattern in both living and non-living systems of self-organization, its role in biological processes exemplifies the involvement of nonlinear elements in regulative self-organization. For instance, oscillations in circadian clocks demonstrate how external contingency can be internalized.

Oscillations are rhythmic patterns that can occur as a result of delay or nonlinearity in feedback loops (Bechtel & Richardson, 2010). Biological rhythmicity is vital for the organism, as it has a fundamental role in the functioning of the heart, brainwaves, respiratory behavior, circadian rhythm, etc. It also appears as regularities at population level such as reproduction cycles. Bodily oscillators are key to understanding how biological form depends on the unification of different rhythms, and how the relative stability of form is coupled with more dynamic processes. Due to oscillators, organizational processes at different levels are tuned with each other, e.g. heart rate is co-determined by the organ and the regulative mechanisms of the whole organism (Longo & Montévil, 2014, p. 183). Synchronization dynamics and nonlinear interactions explain how the fluid layer of organization in physiology is tuned with genetic expression due to oscillators in developmental processes. Oscillations through developmental processes serve as a clock that determines how temporality is directly expressed in the material realization of the form, whereas physiological oscillation is a bridge between external fluctuations and the organism's internal pacemakers.

Biological oscillators have a main role in the developmental phenomenon known as heterochrony. This concept refers to the role of developmental timing in determining the form of the organism, as the beginning, ending, duration, or rate of developmental processes are reflected in the basic characteristics of the body plan (Reilly, Wiley, & Meinhardt, 1997). The role of developmental clock mechanisms has proven that heterochrony is involved in the embryo's measuring time (Keyte & Smith, 2014), and oscillatory patterns are highly influential in the timing of development. For instance, the oscillator that is involved in the development of the snake embryo is much accelerated compared to the mouse embryo, which leads to longer vertebrae in the former (Held, 2014). It has been observed that in the case of ectopic embryo development, body segments can be formed without the oscillation serving as a clock, which is explained by a lower-level self-organization due to cell-to-cell communication that creates the somites (body segments). In normal embryo development, the role of oscillation is to couple the wave behaviour of the whole with the timely subdivision of each body segment (Dias, de Almeida, Belmonte, Glazier, & Stern, 2014).

Oscillation of the calcium level in the cytoplasm is shown to be a factor in gene transcription, as it is found that the frequency of oscillation creates specific patterns of transcription (Roux-Rouquie, 2000, p. 3). Moreover, dynamic states of cells can be induced via the epigenetic mechanism of cell type switching. A cell can have different steady states, and these alternative states can be induced by the microenvironment of the cell, as the autoregulatory transcription is performed via signaling transduction pathways out of the cell (Newman & Forgacs, 2005, p. 59). When cells of a multicellular organism divide, they inherit not only their components as they are, but also their dynamical states, which "can be transient, stable, unstable, oscillatory, or chaotic (Newman & Forgacs, 2005, p. 53). These states are referred to as epigenetic states, since the inheritance between cells is not due to the sequence of genes, but dynamic biochemical states. Dynamic states are not always directly inherited, and sometimes certain interfering factors during cellular division can divert the cells from the current attractor state to another. The propagation of certain epigenetic states is essential to the creation of diverse cellular types during development. Oscillation is a main pattern as an inherited cellular state, as this type of cellular state is involved in cyclic processes in development that might create synchronization, clustering, or symmetry breaking.

The role of biological oscillation is not limited to development. The circadian clock is a key example of the autoregulatory characteristic of the physiological organization. The key function of the circadian clock is to regulate the biological activities of the organism throughout the 24-hour cycle. The circadian clock is self-sustaining, which means that it keeps its periodicity even if there is no external input (Sancar et al., 2010). Biological activities that are regulated by the circadian clock continue with a period that is close to 24 hours in the laboratory conditions of constant darkness. The circadian period is effective at multiple levels of organization from the behaviour of mammals to enzyme activities (Pittendrigh, 1993). The underlying mechanism includes a main endogenous oscillator and peripheral oscillators, sustained by feedback loops and several internal and environmental inputs. In mammals, the central controller of circadian rhythm is the suprachiasmatic nucleus, which is a part of the brain situated in the hypothalamus. Internal oscillators of the clock are synchronized within a structured hierarchy, and even one cell can have more than one oscillator (Roenneberg & Merrow, 2001). Pacemaker cells can keep their rhythmicity in vitro, but this is different from networks. Therefore, rhythmicity is generated at the cellular level, but adjusted at the organism level (Roenneberg & Merrow, 2001, p. 1687). Hormonal rhythms, sleeping behaviour, heart rate, and as revealed more recently, DNA repairing activity (Hogenesch, 2009; Sancar et al., 2010) are regulated according to the circadian clock, which uses mainly endogenous oscillators but also environmental inputs such as light to adjust the clock of the organism. This type of re-adjustment between different oscillation periods is known as entrainment (Golombek & Rosenstein, 2010). Moreover, it has been found that the genetic networks that constitute the clock have an active reorganization capacity after specific genes are knocked out (Baggs et al., 2009), which is quite similar to the examples of the knockout experiments that were discussed in the previous section.

As a self-sustained process, outputs of the circadian rhythm, such as the secretion of melatonin hormone, which regulates sleeping, can affect the receptors of the circadian clock. Input variables of this rhythm can also be under the control of the circadian clock (Golombek & Rosenstein, 2010). Pittendrigh (1993), who is one of the pioneers of research on circadian clocks, asks why organisms need a daily rhythm to regulate their activities. As an answer, he points to “organization that exploits the reliability of the external day as a time-reference and whose goal is an appropriate sequencing of diverse internal events rather than the concurrence of internal and external events” (Pittendrigh, 1993, pp. 30-31). The evolution of an internal clock mechanism gave an anticipatory advantage for predictable changes (Golombek & Rosenstein, 2010). According to a hypothesis, the first circadian clock might have evolved in ancient aquatic organisms to regulate their vertical movement in order to avoid the harmful effects of UV light (Pittendrigh, 1993). The discovery of the genetic connection between the repairing activity against UV radiation and circadian regulation supports this hypothesis (Sancar et al. 2010).

The role of oscillatory clocks in development, epigenetic regulation, and physiology reveals how time is embraced internally. Based on this, claiming that time for the organism is subjective would be an excessive claim that would share a similar idealism with autopoiesis. Yet, it would be reasonable to conclude that time has a subjective aspect that is realized through the ontological distinction between the internal and the external. Above, I defined the synchronic and diachronic conditions as relative to each other. In this sense, for example, entrainment in the circadian oscillators is a synchronic condition relative to the role of the oscillatory clock in developmental segmentation, which in contrast corresponds to a diachronic condition. This is because the realization of the former appears as a bridging between short-term stabilization of the internal physiology and the external fluctuations. The latter is diachronic in so far as temporality is materialized in the body segments, which implies a lifetime influence within the diachronic extension. In the examples of oscillation discussed in this section, it also becomes apparent that the coupling of different paces of change determines the dynamic nature of the organism’s form that is extended in time. On this basis, more solidified and more fluid aspects of biological organization become united, allowing the co-existence of the contingency and relationality elements.

Conclusion

In this chapter, I examined the philosophical problem of emergence in the context of the organism’s self-organization. I concluded that emergence is ontological, as it is based on the processual and relational nature of causal relations. The constraint interpretation suggests that emergence depends on the contingent formation of relationality. This implies that universal laws only determine the necessitarian basis of relationality. Yet, relational dynamics within a local system are not exhaustively predetermined by the laws of nature, hence they are emergent. Self-organization supports the arguments for emergence on the basis of individuation. The process of individuation refers to the contingent formation of reciprocal relations, which leads to the creation of coherent structures. The emergent nature of the organism involves more complex processes compared to non-living systems. The organism can use its internal potentiality throughout its individuation. This characteristic of the organism supports the idea of diachronic emergence. The organism's synchronic condition cannot be considered as distinct from diachronicity. On the other hand, although diachronicity is based on individuated processes, individuation is limited by the synchronic condition that disguises the unformed state, which is the source of potentiality. My argument concerning the synchronic irreducibility of a time sequence of organization needs to be supported by further empirical sources in addition to my focus on oscillation. Moreover, my account should be scrutinized in relation to other philosophical problems, such as the further implications this has for the levels of organization.

Another conclusion of this chapter relates to the notion of dynamic form. Formal causation is not applicable to the organism's self-organization without engaging with its broader context in Aristotle's philosophy. Therefore, contemporary appeals to formal causation are problematic. Form and matter do not correspond to ontologically distinguishable aspects of organization. Form originates in the individuated characteristic of relationality, which depends on the temporary nature of processes, but not absolute properties. An atomistic conception of matter associates the notion with static entities at the lowest level within the hierarchy of organization. However, since matter is always relational and processual, this understanding of ultimate particularity is incorrect. In the context of biological form, dialectical unity of contingency and relationality is essential. On this basis, I criticized approaches that are biased towards reducing the explanation to either side of these co-existent features. Genetic reductionism ignores the contingency aspect by adopting a preformationist perspective. An interpretation of structuralism that is solely based on the laws of form also disregards contingency within the historicity of organisms. On the other side, DST is problematic, as it exaggerates the role of contingency and underestimates the underlying factors of formal stability. In addition to these theories in biology, I critically examined the historical and philosophical basis of mechanistic explanation. Mechanistic approaches cannot explain biological processes because the way it models causal relations is inconclusive in terms of embracing the implications of recent scientific developments and the causal nature of biological processes. Therefore, it is necessary to seek out a new scientific approach that considers the fundamental claims for causation that reside in biological processes.

I offered an account of self-organization that emphasizes the potentiality of interrelations as opposed to accounts that attempt to eliminate the emergent aspect of biological organization. My primary aim was to demonstrate that temporality plays an irreducible role in organization. I also argued that regulative self-organization needs to be defined due its unique characteristics in ontogeny. On this basis, I claimed that there are several ontological connections between the universal dynamics of emergence and the way that temporality is embraced in the organism. I have demonstrated that the transitional dynamics of self-organization permeate into both biological and non-biological systems. This supports the idea of the universality of self-organization.

General Conclusions

Lifetime is a child at play, moving pieces in a game. Kingship belongs to the child.

Heraclitus, *Fragments,* XCIV

In this thesis, I discussed the self-organization of the organism in the light of a relational ontology. The two postulates that I adopted due to this ontology were: *i.* everything is relational and there are no absolute properties that can be realized in isolation, and *ii.* there is a limit to spatially and temporally decompose a synchronic condition, i.e. an unformed processuality underlies individuality. These postulates were the bases of my inquiry into various forms of biological processes. Concerning the organism's organization, I claimed that ontogeny is a process of individuation. Individuation refers to the general tendency for self-organization due to the establishment of reciprocal relations in a condition of multiplicity. I have demonstrated the validity of this description of self-organization by explaining various theories, models, and experiments in biology. This analysis also covered the examination of research in physics to a certain extent. My main motivation was to prove that emergence is ontological by drawing support from the theory of self-organization. This was contrasted with the position that reduces emergence to an empirical issue concerning the configuration of parts within a whole. An atomistic conception of lower-level components underlies this type of reductionist attitude toward emergence. Instead, I defended a process philosophy, and drew attention to the problems posed by the atomistic and mechanistic conception of causal relations. As an alternative, my account of potentiality helps to overcome these problems by identifying how they are derived from an inconsistency between mechanicism and biological relationality. On the other hand, the irreducible synchronic condition of living processes, which refers to the unshaped fundamental level of individuation, is the underlying theme of potentiality. The organism's hierarchical organization serves to utilize the potentiality that arises within lower levels. The coupling of the synchronic condition to the diachronic elements is key to understand how the contingency and the lifespan organizational robustness can co-exist within the dynamic form. The synchronic condition is temporally irreducible, heterogeneous, and partially unformed, including potentiality for multiple states. The diachronic condition is the sum of organizational processes including homeostatic control, medium-term and long-term determinations, centralized functions, anticipatory elements, and so on. This temporally extended condition finds its organizational potentials within the synchronic state, which denotes the current actualization of the lifespan development that is under constant individuation. As suggested by Gilbert Simondon, individuation implies an unachieved state of individuality.

The theoretical account that I developed from these principles was applied to the notion of regulative dynamics of self-organization within the organism. This systematic view justifies diachronic emergence in the context of scientific theories. The organism is in a far-from-equilibrium condition, and a constant energy flow is necessary for its survival. The organism's form is dynamic throughout the energy flow. Continuity of form is double-edged, as it is based on tolerating perturbations as well as utilizing contingent factors to expand its organizational possibilities. This double-edged dynamicity of form has interesting implications in terms of contingency and relationality in a broader context. The constraint interpretation of emergence correctly identifies that the laws of physics cannot predetermine the actuality of causal relations (Polanyi, 1968; Blachowicz, 2013). This leads to the idea that relationality, which is the ontological condition of organizational constraints, has an irreducible aspect of contingency. Relationality also has an aspect of necessity due to the law-like nature of causal relations. However, the aspect of historical contingency is not directly imposed by the laws of nature, as the latter is context-free. When this idea is applied to the form of the organism, it would be possible to reveal the close link between contingency and emergence. On the one hand, in so far as an entity is organizationally stable, its relationality is to be deduced as a direct application of the laws of nature. On the other hand, organizational dynamism provides openness by enabling the discovery of new internal relationalities, and the emergent relational wholes become detached from simplistic expressions of physical necessities determined by the laws of nature.[57] Thus, the organism's potentiality serves to continuously invent its own form through a process of individuation. This is the condition of epigenesis within the organism's form, which also indicates that universal dynamics of emergence are involved in the processes of ontogeny.

The claim that the organism uses its potentiality that I asserted above and previously brings with it the philosophical questions around the notion of agency. Even though I did not refer to this concept extensively throughout this work, the indirect expressions that evoke the notion of agency are also quite controversial. This is mostly because agency is often thought to be within the scope of a theory of action dealing with the phenomena based on mental representations. Therefore, extending the notion by including non-cognitive situations is found to be problematic. While conceding that human agency marks a philosophical area that can be investigated per se, I believe that presupposing agency as restricted within human acts disguises an assumption of the existence of an ontological rift – or at least an ontological leap – between human agency and its naturalistic basis. This kind of ontological rift might reflect a sceptical attitude towards the scientifically illuminable connection between human agency and its naturalistic basis, e.g., this kind of sceptic might believe that evolutionary background of cognitive abilities has nothing to with the analysis of normative and practical standpoints. Or, a reductionist attitude attempting to explain – or explain away – the emergent aspects of human agency might underlie this misconception of the ontological rift, as this kind of reductionist would believe that in so far as a mechanistic explanation of the human agency is provided, any philosophical issue that is related to it, e.g. the reconciliation of the teleological nature of mind with naturalistic explanations, could also be resolved by untangling all these issues through the established understanding of causation.

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[57] As mentioned before, a radical interpretation of this idea suggests that established relationality is a new law-like situation (Mitchell, 2000).

However, the notion of self-organization also involves questioning these strong philosophical convictions. Also, self-organization provides possible explanations for cognition and human agency. Therefore, it could be possible to reach new understandings of causation by applying self-organization to the questions of human agency. This also paves the way to a unified perspective bridging agency and a naturalistic analysis of complex systems without reducing the former to the latter. Agency is due to emergent properties of matter, and considering the multi-dimensional emergence of complexity from the primitive conditions of Earth to living systems and social structures, agency also reflects a capacity within matter for the appearance of qualitatively new dimensions of evolution. Vice versa of the abovementioned reasoning from the self-organized nature of human agency to new types of causation is also true: different complex systems involving extraordinary causal powers share a common ground with human agency. Autopoiesis has asserted this claim for organisms in general, as it is argued in this theory that simple organisms such as bacteria exhibit agency without mental representations comparable to those of humans (see Chapter 2). From the perspective of a generalized view of self-organization, agency is an extensive phenomenon due to an individual's capacity to act upon itself as well as upon the external conditions, and the agency due to human mind is an advanced manifestation of this capacity. Sure enough, one can adhere to a narrow context of agency that is defined on the basis of deliberate acts, but this restricted description would reflect just the tip of the iceberg. It should be emphasized once again that goal-directed activities of the organism have a wider scope than intentional actions.[58]

The abovementioned ideas can be justified depending on empirical studies and theories regarding living systems and processes of self-organization. Emergent order in the ontogeny of the organism is evident in the materialization of nonlinear dynamics. The emergence of attractor states, self-organized criticality, the formation of patterns, and the building of complexity within an ecosystem are

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[58] Embryonic induction is a good example of this. Spemann's experiments have shown how the cells of a transplanted embryo are capable of becoming organizers by recruiting cells from the host embryo (see Niehrs (2011) for details).

determined by an unprecedented development of reciprocal relations. In this regard, they fall into the category of transitional self-organization. On the other hand, the organism's self-organization is regulative because the organism, as a product of evolution, involves a special condition of organization. From the beginning of embryological development, the organism is determined by organizational constraints. The organism uses inherent potentials via an organizational hierarchy in which there is a reciprocal relation between bottom-up emergence by spontaneous dynamics of order and top-down determination by centralized functions. Cellular differentiation also exemplifies lifespan potentiality. Moreover, the organization of the organism incorporates nonlinear dynamics, which is evident in the role of biological oscillators in cell states, developmental rhythms, and circadian clocks.

I argue that this sufficiently demonstrates that emergence is ontological. An emergent condition corresponds to real novelty that is not preformed. However, there are differences between the strengths of the subsidiary claims that I have made. Certain ideas in relational ontology are quite obvious: Nonlinear systems indicate that the reciprocal relation between a component and the system it belongs to is context-dependent. Reciprocal relations are widespread and fundamental in living systems. Nevertheless, when it comes to the question of radical implications of relationality, the issue is rather controversial. I claimed that relationality negates both the notion of absolute properties, and that things are the sum of their relations. These claims suggest that relational ontology has profound implications concerning the nature of reality. Thus, my argument requires additional support from a discussion of relational ontology based on the relevant ideas in general philosophy of science (and philosophy of physics in particular). This was beyond the scope of my thesis, as I could only briefly engage with this area in the introduction and the fourth chapter. A similar point can be made in relation to process philosophy. My claims that temporality of the synchronic condition of the organism is not reducible, and that it is connected to the diachronic elements of organization need more verification by an examination of the studies in physics. This is a claim that I made depending on the processual nature of things, but it can be criticized for falling into a tautology due to the circular nature of reasoning between process ontology and irreducible synchronicity. I attempted to avoid this kind of circularity by emphasizing that the empirical findings concerning the relational and processual nature of biological systems in fact support arguments relating to the nature of causation. As emphasized by the proponents of relational biology, certain causal capacities only emerge in living systems. Therefore, research in biology cannot be deemed subsidiary to physics, and there is potential scientific support for a process ontology also in biological research.

As a final theme of this concluding chapter, I will suggest some potential paths that can be developed based on the philosophical investigation in this thesis. One of these expansions could be the application of the idea of potentiality to functions. The philosophy of functions is a wide topic that involves discussions concerning artefacts and the adaptive traits of living systems. Functions have been discussed in relation to issues that have been addressed in this thesis, including biological autonomy (Mossio, Saborido, & Moreno, 2009), natural selection (Wright, 1973, 1976), and self-maintenance of living systems (McLaughlin, 2001). Two different accounts of functions involve: *i.* etiological theories, which depend on an analysis of the history of adaptive traits, and *ii.* dispositional theories, which depend on the current performance of the function (Wouters, 2005). There have been attempts to overcome the dilemmas due to this dual nature of explanation and develop a unified theory of functions (Godfrey-Smith, 1994; Mossio et al., 2009; Artiga, 2011). Wright (1973) proposed an etiological theory of functions based on selected effects. According to this idea, a cause-effect relation might turn into a function when the effect of the cause enables the causal agent to persist in time. In *Teleological Explanation* (1976), Wright developed this idea further by attempting to offer a naturalistic account of teleology. He added the condition of the indeterminacy of mechanical causes in this analysis. Concerning biological processes, Wright applied this idea only to natural selection. However, I believe that this theory of functions can include a wider scope of biological processes. Also, beyond an etiological theory of function, there is a possibility to reformulate relevant ideas as a unified theory of functions. Wright's ideas can be interpreted in terms of a theory of potentiality. Similar to Wright's emphasis on the indeterminacy of mechanical causes, the potentiality view that I promoted in this thesis involves a certain degree of indeterminacy that is inherent within individuals. Moreover, the understanding of centralized functions within the organizational hierarchy depends on an idea that lower-level dynamics constitute organizational potentials, and an internal selection operates due to goal-directed operations of the organism's functionality. In this way, selected effects can be considered in the context of the organism's organization.

The theory of Waddington provides another possible way to further develop the claims in this thesis. Waddington coined the term "epigenetics" as a combination of the words of epigenesis and genetics. He pioneered a comprehensive application of the idea of potentiality to biological processes. Waddington considered the genotype as a set of potentialities that are actualized through development (Van Speybroeck, 2002, p. 69). In this sense, Waddington's theory involves the expanding of Driesch's view defending the potentiality of embryonic cells against preformationism. Waddington was influenced by Whitehead's philosophy that promoted the ideas of potentiality and relationality (Gare, 2017). It is claimed that Waddington's support for this philosophy might have contributed to his exclusion from the orthodox circles of neo-Darwinism in his day (Peterson, 2011). Waddington's approach relates to the problems of this thesis due to both dimensions that I explained in the introduction: the dimension of philosophy of biology that includes the critique of neo-Darwinism and the dimension of the theory of causation that includes the idea of potentiality. Thus, related ideas in the accounts of Waddington's biology and Whitehead's philosophy deserve more attention in order to make a strong case in favour of potentiality and relationality.

The final theoretical path that might contribute to the expansion of the ideas in this thesis is biosemiotics, which was pioneered by Friedrich S. Rotschild, Charles Peirce, Charles Morris, Thomas Sebeok, and Jacob von Uexküll. More recent applications of biosemiotics involve an investigation of living systems due to an emphasis on their information-dependent characteristic (El-Hani & Emmeche, 2000; Queiroz, Emmeche, Kull, 2007; Kull & El-Hani, 2011). A study of biosemiotics could be promising due to the understanding of potentiality within this theory. According to the Peircean understanding of potentiality, the universalist conception of the laws of nature is misleading. Instead, the local law-like principles are implemented within the mediating system. There are alternative stabilizations of the form within the tripartite interactions between the sign, the interpreter, and the object, which are all relatively determined. The alternative interpretations that appeal to tripartite relationality identify how a synergetic variability can be exploited by the whole system in which these elements are involved. Based on this view, Stanley N. Salthe (1985, 1993) proposed a theory of organizational hierarchy concerning living systems, and pointed out that self-organization is a multi-level phenomenon (Salthe, 2013). He also investigated the universal implications of the idea of self-organization. Salthe states that self-organization relates to systems that change both evolutionarily and developmentally. Self-organization denotes an inner directive power within the system, and it is originally a Hegelian idea as an alternative to the Newtonian understanding of causality (Salthe, 1989, p. 201). An analysis of Salthe's approach to self-organization requires engaging with its Peircean basis, which can be accomplished only within a project mainly focusing on the issue, due to the depth of its theoretical origins.

This thesis addressed the philosophical issues with self-organization with an aim of emphasizing the need for a new theoretical perspective in biology. Although there is a vast literature appealing to the notions of self-organization, emergence, and potentiality,[59] some of the relevant studies in fact tend to neutralize the causal implications of these concepts and suggest going back to the view of mechanical determinism. To avoid this, a philosophical discussion of relationality must involve a questioning of the established understandings of causation perpetuating under the misleading cover of common sense. Even when it is considered that certain presuppositions concerning causation are based on either a priori knowledge or direct empirical analyses,[60] it is highly likely that certain convictions due to traditions in history of science and daily understandings of the world permeate our background assumptions. A good way to prevent this burden is to bite the bullet and admit that observation is theory-laden. Then, it would be possible to recognize

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[59] Potentiality is not as popular as the other two concepts, whereas ideas related to potentiality are gaining more attention due to studies discussing dispositions, possibilities, and causal powers.

[60] Obviously, these are in contrast with each other. Still, both exclude the involvement of previous theories in different ways.

traditionally constructed aspects of our claims about causality, which creates an opportunity to deconstruct them. The denial of self-organization is mostly led by the conviction that something cannot act upon itself. Processes of individuation suggest the contrary.

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